Assessment of Impact of Offshore Wind Energy Structures on the Marine Environment

Prepared for

The Marine Institute

by

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Volume I

Main Report

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Summary

The Marine Institute commissioned this study to examine the impact of offshore wind energy structures (wind farms) on the marine environment. This desk study was conducted by a project team comprising Byrne Ó Cléirigh, EcoServe, and the University of Southampton. In accordance with the Terms of Reference, the study was confined to examining the "below the water" impacts on the marine environment. It is not intended to address the impacts of any particular type of wind farm in any particular location. The Terms of Reference requested a review of current knowledge on artificial reefs. This is presented in a separate volume (Volume II).

The study findings indicate that the offshore wind farms, which have been built to date in Denmark and Sweden, have had little negative impact on the marine environment. On the basis of the experience to date Denmark plans to increase its installed wind power onshore and offshore to 50% of its requirement for power by 2030. Five major offshore wind farms each of 150 MW will be built in Danish waters within the next five years. This is a major part of Denmark's plans to meet its international obligations on Greenhouse Gas Emission Reductions.

Current technology sets an economic limit on offshore wind power projects to areas with water depths less than 15 metres and within reasonable distance from the electricity grid. These economics are reflected in Ireland by the current interest in offshore wind farms in the waters off the east coast in areas where reefs and banks provide sites with a combination of acceptably low water depths and within an acceptable distance offshore.

The literature suggests a trend, based on cost, towards selection of monopile foundations where the turbine tower is connected to the seabed by a single steel pile. The footprint of the foundation using monopiles will represent only a small fraction of the sea area occupied by a wind farm. A monopile foundation will be 5 metres in diameter and the space between individual turbines may be up to 500 metres. Other foundation types such as gravity caisson will occupy a larger area than a monopile footprint (up to 15 metres diameter) but even these will represent only a small fraction of the overall area of the wind farm. Thus the loss of physical seabed habitat during the operational phase of a wind farm would be minimal. Disturbance during construction will however have to be minimised and protocols will be needed to ensure that proper controls are in place.

Offshore wind farms may have underwater environmental impacts before construction (e.g. seismic surveys), during construction of the foundations and laying of electrical cables, and during operation. Some impacts can be mitigated through care in site selection, foundation design, and operational planning. These would include effects on navigation and the impacts of waste disposal. While it is not expected that turbine foundations will have a significant effect on water currents, these currents and the tides may have implications for planning construction work and site maintenance. The effects of noise from the turbines, and electromagnetic radiation from the cables, on marine life also need to be considered.

Trawling may be prohibited from near the turbines and cables, but the wind farm area may be designed to benefit other fish stocks. This design may consider the

construction of artificial reefs as a mechanism to improve fish stocks, such as lobster, or as a mechanism to prevent trawling over cables and seabed habitats of importance to other commercial species (e.g. scallops). The habitat protected from trawling may become a refuge for young and spawning fish and thus provide benefits to the fish populations beyond the immediate exclusion area.

Changes to seabed habitats caused by foundations, cables and other works (e.g. rock armour, artificial reefs) would have implications for fish stocks and marine life on the seabed and in the water column. These would include indirect effects on species which feed on species living in these habitats, such as larger fish, birds and sea mammals. However, these changes can be positive, and designed to improve habitats for species of fisheries or conservation importance. This report describes the potential benefits to fisheries, angling and nature conservation, that may be derived from fishery exclusion areas and artificial reefs.

The study makes recommendations to assist the Marine Institute and the Department for the Marine and Natural Resources to ensure that the generation of electricity in offshore wind farms is achieved with minimum impact on the marine environment and to mitigate these negative impacts and enhance the potential for positive impacts.

A wind farm with multiple turbines will involve a network of cables, with a cable linking each of the turbines to a transformer tower and then to land via by higher voltage cable. Protocols will be required to ensure that no damage to cables is caused by anchors or fishing gear. In view of the practical difficulties of monitoring the movement of vessels passing over a network of cables it may be necessary to consider exclusion zones for certain types of vessels operating over the whole wind farm. The imposition of such zones would not, of course prevent the development of fish stocks within the area of the wind farm and may indeed enhance overall fish stocks. In the context of exclusion zones, the turbines themselves will provide the clearest possible delineation of the area concerned. However, any policy on such exclusion zones will have both positive and negative impacts. Thus while the use of protected areas may well increase fish stocks overall, it may limit fishing in the immediate vicinity.

The study recommends a programme of research. Because of the current economics, the proposal is to concentrate initially on the east coast and in particular on the shallow banks close to shore. The research should include:

- A study of the ecology of the offshore banks with particular reference to species of economic and ecological importance;
- The dynamics of shallow banks on the east coast of Ireland;
- The effects of fishery exclusion zones on local fisheries.
- The effects of artificial reefs on offshore ecology (particularly spawning beds and nursery areas);

There are several other areas not well reported in the literature. We have suggested that the Marine Institute should also consider research in these areas. One is the potential impact of undersea cables on fish stocks and the behaviour of marine species. The other is the transmission of vibrations from the turbine towers into the water column. Neither of these topics has been reported in the literature seen to date. The results of baseline surveys and biological monitoring at wind farms should be published to provide data to confirm the predictions in an EIS and contribute to general knowledge of the environmental impacts of wind farms.

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1. Introduction

1.1 Background

The objective of the study was to present the Marine Institute with a desk review of the current stated knowledge on the impact of offshore wind energy structures on the marine environment. The study was completed between September and December 1999 by means of a series of tasks, which had been set out in a proposal submitted to the Marine Institute (BÓC Ref. 99A0279).

The Report is structured to provide the data generated by the study under a number of main headings. These include:

- Physical impacts of wind farm structures;
- Potential for offshore wind farm structures as sites for artificial reefs;
- Impacts of structures on the biology of areas in which wind farms may be built.

The report is laid out as follows. Section 2 of the Report places the current interest in offshore wind farms in a European context. It highlights the rapid speed of development in offshore wind farms in Europe. Section 3 present the review of existing information on the main technical areas of physical impacts and biological impacts. Section 4 sets out the positive and negative impacts of offshore wind farms and lists the concerns of consultees as well as listing the impacts and possible mitigation measures.

The report then makes recommendations for actions that the Marine Institute could take to ensure that the generation of electricity in offshore wind farms can be done with minimum negative impacts on the environment. These recommendations could be used to develop conditions in leases and licences (Section 5), and to propose areas for further research (Section 6). A review of current knowledge on artificial reefs is presented in Volume II.

1.2 Methodology

A range of organisations with an interest in offshore wind energy developments were contacted, and some were consulted to assess their concerns in relation to offshore wind farms. These included developers, regulators, other marine resource users and environmental organisations (Table 1). It is anticipated that prior anticipation of the concerns expressed will facilitate the inclusion of measures to avoid, or mitigate these issues.

This study reviewed information available from published sources and web sites. The Danish Wind Turbine Manufacturers Association (web site www.windpower.dk) proved a most useful source of information. The Irish Sea Forum held a seminar on offshore renewable energy in Llandudno on the 18^{th} and 19^{th} October 1999, which brought together knowledge and fostered discussion on the development of offshore wind farms.

Table 1. A list of the organisations contacted as part of the present study.

Government	Industry	Environmental	Members of the Irish Offshore Coalition
Department of the Marine and Natural Resources	Irish Fishermen's Organisation	BirdWatch Ireland	Campaign Whale
Department of Public Enterprise	Saorgus	Environmental Sciences Association of Ireland	Coastwatch Europe
Department of the Environment, Transport and Regions (UK)	Powergen Renewables		Friends of the Irish Environment
Marine Institute and MI Fisheries Research Centre	Harland and Wolff		Irish Wildlife Trust
Bord Iascaigh Mhara	British Wind Energy Association		Irish Women's Environmental Network
Central Fisheries Board	Danish Wind Turbine Manufacturers Association		Joint Links Oil and Gas Environmental Consortium
Duchas - The Heritage Service			Voice of Irish Concern for the Environment
Met Éireann			An Taisce
Irish Energy Centre			
Danish Energy Agency			

2. Offshore Wind Farms in Context

2.1 Overview

It is European Union policy to increase the share of renewable energy to 12% in 2010. Some of the Member States have announced ambitious plans indicating how they intend to achieve this target.

Wind energy will play a major role in achieving the EU targets for renewable energy. There is 11,000+ MW of onshore wind energy capacity installed to date in Europe. Recent technological advances, more favourable wind conditions at sea, and environmental concerns regarding visual and noise impacts in relation to onshore wind farms have prompted the development of offshore wind farms. There are five offshore wind energy projects operating in Europe at present. These are concentrated in Denmark and Sweden.

Denmark plans to have 4,000 MW of offshore wind energy installed by 2030 (Baker 2000), and by then aims to produce 40% of the country's power requirements from offshore wind farms. To accommodate this they will need to radically modify their electricity distribution system. The Danish plans are possible, in part, because of their policy of decentralised electricity generation (widespread use of Combined Heat and Power) and also by co-operation agreements with Norwegian power companies to supply hydro power when the winds are slack in Denmark.

The Netherlands is aiming for 1,360 MW of offshore wind power by 2020. Finland has assessed the technical potential of offshore wind in the Gulf of Bothnia in an area of 2,000 km^2 as 17,000 MW. These plans can be viewed against the projected increase in power requirements in Ireland over the next 10 years during which an additional 4,000 MW of generation capacity may be required at current growth rates.

Generating electricity from wind farms avoids the emission of harmful pollutant gases that would otherwise be emitted from conventional thermal generating stations burning fossil fuels. The most significant of these gases are oxides of sulphur and nitrogen, and carbon dioxide, which is a major contributor to the total of man-made emissions of greenhouse gases. The electricity generation sector in Ireland emits 14 million tonnes of CO_2 per annum. Wind farms emit no CO_2 during operation. Generating electricity in a 200 MW offshore wind farm operating at a 30 % load factor would avoid the emission of:

- 514,000 tonnes per year of CO_2 compared with the 'average' existing emissions across all thermal plants, or;
- 246,000 tonnes per year of CO_2 compared with the least polluting existing thermal plants (gas fired combined cycle gas turbines), or;
- 780,500 tonnes per year of CO_2 compared with the most polluting thermal plants (older peat fired plants).

There are five different consortia reported to be considering offshore wind farm developments in Ireland and fifteen in the UK. The total Irish grid currently has a peak capacity of ~ 4,000 MW. The Irish coastline is 7,524 km long (Neilson and Costello, 1999). Even allowing for the need to protect navigation channels, special marine areas and areas of scenic beauty, the technical potential of offshore wind farms in Irish waters is very large and could even lead to significant exports of power in the long term.

A consortium is examining a project to build a 200 MW wind farm on the Kish Bank in Dublin Bay. The area of interest is reported to be 8 km long by 2 km wide and with water depths of 2 metres at their shallowest. A foreshore license has been applied for and a twelve-month feasibility study is ongoing. The wind resource is currently being measured using wind instruments mounted on the Kish lighthouse (which is located on the northern tip of the bank). Local bird populations are also being studied.

The Department of Public Enterprise commissioned a report to establish the technical and actual potential for offshore wind energy. This work was proceeding in parallel to this study and was not available for consideration by the present study team.

The current trend in offshore wind farms is towards large turbines in the 1.5 – 2 MW range (Farrier 1997). Typically these turbines would measure up to 100 m from sea level to the blade tip (i.e. when blade is in vertical position). Hub heights would be approximately 60 – 70 m above sea level.

The principal issues to be considered when selecting a site for an offshore wind energy development are:

- Nature of wind resource;
- Sea bed structure;
- Water depth;
- Distance to shore;
- Distance to service port;
- Distance to grid connection;
- Tides and currents (which may be spatially and temporally variable at any site);
- Shipping;
- Recreational boating;
- Location of existing subsea cables and pipelines;
- Fisheries;
- Areas of high conservation significance;
- Density, diversity and behaviour of local bird population;
- Density, diversity and behaviour of local marine mammal population;
- Dredging;
- Coastal landscape;
- Local military activity (e.g. firing ranges, offshore training);
- Potential for aggregate extraction.

There is good potential for offshore wind farm development in Irish waters. At the moment interest is primarily concentrated on the east coast (Annex 3). The main reasons for this are:

- Less severe wind and wave loading than the Atlantic coasts;
- Accessibility to electricity market;
- Accessibility to grid connections
- Existence of shallow water banks including the Kish, Codling and Arklow banks;

- Compared with other parts of Irish Sea, there is an excellent wind resource along some of these banks.

2.2 Current Position on Permitting in EU States

Ireland

Before an offshore wind farm site may be developed in Ireland approval must be sought from the Department of the Marine and Natural Resources for a Foreshore Licence and a Foreshore Lease under the Foreshore Act. When considering a Foreshore Licence certain areas will be prohibited for use as generating stations where safety at sea, protection of established shipping lanes, air navigation, telecommunications needs, gas pipelines and/or defence requirements demand it (Annex 2).

Nature conservation areas for birds, called Special Protection Areas, have been designated in many estuaries, islands and headlands around Ireland. As part of the Natura 2000 network of nature conservation areas in the European Union, these SPAs will be complimented by Special Areas of Conservation, which will include marine areas. In addition to such protected areas, some species such as cetaceans, seals and birds, are protected wherever they occur. Species and areas of nature conservation importance will need to be considered in relation to the siting and operation of offshore wind farms. However, wind farms may not only be compatible with nature conservation but assist its protection and monitoring within the farm area. Shipwrecks and other items of archaeological importance may occur within proposed areas for wind farms, or along cable routes. Prior consultation with Dúchas, The Heritage Service, with regard to both nature conservation and archaeology is thus necessary in planning an offshore wind farm.

Licences to generate and to supply electricity and an authorisation to construct a generating station must be obtained from the Commissioner for Electricity Regulation. Planning permission is required for any onshore structures from the appropriate Local Authority. An Environmental Impact Statement (EIS) is now required for an offshore wind farm development whose total output exceeds 5 MW or has 5 or more turbines. The present report will assist the scoping of what should be included in an EIS.

England and Wales

The Crown Estate owns 50% of the foreshore and tidal rivers, and 99.9% of the seabed below mean low water (MLW) out to 12 nautical miles from the English and Welsh coasts (Jacobson 2000). It also owns the rights to all national resources (excluding hydrocarbons) on the continental shelves extending from these territories.

The following consents must be gained before offshore wind energy may be developed at a specific site in UK waters (Trinick 2000):

- Right to place works in navigable waters from the Department of Transport and Regions (DETR);
- Licence to deposit articles on the sea bed from the Ministry of Agriculture, Fisheries and Food (MAFF);
- Consent from the Department of Trade and Industry (DTI) if the planned farm is more than 50MW (under the 1989 Electricity Act);
- Planning permission;

- Consent to place works in a 'main river';
- Permission from Harbour Authority.

In an attempt to streamline the process in Britain it is intended that a Transport and Works Act order combined with a Food and Environment Protection Act license will deliver the consents required (Jacobson 2000). The Crown Estate will lease the seabed for 25 years and charge a rent of 2% of gross turnover (Jacobson 2000).

Denmark

Denmark plans to install five 150 MW demonstration farms from 2002 to 2005. Developers are offered a 20 year lease and a condition of the lease is that they must provide all information from the farms to the Danish government.

3. Review of Existing Information

3.1 Overview

In this section of the report, the findings of a review of existing information on the physical and ecological impacts of wind energy structures on the marine environment are presented. The impacts underwater relate primarily to the impact of the foundations for wind turbines and the associated electricity cables.

These impacts will need to be considered in the development of guidelines for Environmental Impact Statements specific to offshore wind farms. These guidelines will build on those already published by the Environmental Protection Agency (1998a, 1998b).

3.2 Physical Impacts of Offshore Wind Farms

Foundation Technologies

Securing suitable foundations at an economic cost is the major technical challenge facing offshore wind farm development. Marine foundation technology has been developed for oil and gas exploration, and foundations are typically designed to last 50 years (Walsh 1994). It is noteworthy that this is twice the 25-year (maximum) lifetime of the current generation of offshore wind turbines. These turbines employ the same technology as those developed and tested for use on land. Foundations installed today may therefore be re-used for the next generation of turbines. The three main types of foundation construction are (1) gravity caisson, (2) monopile, and (3) multiple piles.

Gravity Caisson

Both Vindeby and Tuno Knob (Denmark) offshore wind farms use concrete gravity caisson foundations. Hollow concrete one-piece foundations are manufactured in dry dock, floated out to the site and then filled with sand and gravel so that they sink to the sea floor at the desired location. They rest on the sea floor. They may be used on most types of seabed, but seabed preparation is required, and divers must remove silt and prepare a smooth horizontal bed of shingles to ensure uniform loading of the sea bed. In many cases protection against erosion (scouring) is required and is achieved by positioning boulders/rocks around the base of the foundation. The foundations at the above referenced wind farms are conical in shape to help break up pack ice. These foundations are very heavy and require larger cranes during installation than steel equivalents. Their cost is approximately proportional to the square of the water depth. According to Danish Wind Turbine Manufacturers Association (www.windpower.dk) these foundations tend to be too heavy and expensive at water depths greater than 10m.

Alternatively, a steel caisson may be used. A cylindrical steel tube is placed on a flat steel box on the sea floor. It is then filled with olivine (very dense material) to give it necessary mass. Steel caissons are lighter than concrete equivalents and consequently require lighter cranes and barges for erection. Also the cost of moving to depths beyond 10 m is considerably less than for concrete foundations because the base does not have to increase in size to the same degree as the concrete installations. Corrosion is not considered to be a major problem with submarine steel structures as experience from offshore oil and gas installations has shown that cathodic protection is very effective. Cathodic protection may affect the colonisation of marine organisms on steel structures and the issue of fouling organisms may need to be addressed.

Monopile

This foundation consists of a steel pile 3.5 – 4.5 m in diameter driven 10 – 20 m into the seabed using heavy duty piling equipment. Essentially the turbine tower extends underwater and into the seabed. No preparation of the seabed is generally required. However, if large boulders are encountered they must be removed. Piled foundations are not suitable for areas with many large boulders. Erosion (scouring) is unlikely to pose a problem with piled foundations because of the depth below the seabed to which they are driven.

Multiple Piles

These are similar to support structures developed for marginal offshore fields in the oil and gas sector. A steel pile beneath the turbine tower transfers the load to a tripod. Small (0.9m diameter) steel piles secure each corner of the tripod to the sea floor.

Multiple piled structures share the same characteristics as monopile foundations except that they are:

- suitable for deeper sites;
- cheaper than monopiles in deeper water; and
- not suitable for shallow waters as access to towers can be obstructed by tripod structures just beneath the water surface. In deeper waters, deep draught vessels (maintenance and service vessels) must avoid the immediate vicinity of multiple piled structures.

Decommissioning

The processes involved in decommissioning offshore wind farms are dependent on the type of foundation involved. There is no published material on the decommissioning of offshore wind energy structures as they are relatively new developments. However, the removal of monopile and multiple pile structures would be less complex and thus cheaper than the removal of a concrete caisson or similar structures. The removal of the monopile would probably involve cutting the pile at sea bed level.

Undersea Cables

Cables must be buried to avoid damage/accidents if struck by fishing equipment or anchors. Cables may be jetted into the seabed using high-pressure water jets if seabed conditions permit. Otherwise they must be dug or ploughed in (Clarke 1999). Rocky seabed conditions may prevent cable burial within the seabed and cables may need to be buried by covering with rocks. There is extensive experience in laying cables on the sea bed (e.g. Parker 1999), and dealing with their environmental impact (Clarke 1999).

Protocols must be developed to ensure that fishing vessels keep clear of undersea cables. In the USA, AT&T and Pacific Telecom recommend that fishermen remain at least one mile away from their undersea communication cables. This would result in a two mile “no fishing” area along the cable corridor.

Electromagnetic fields may emanate from undersea cables and there are concerns that they may affect wildlife (Doyle, 2000). There is no empirical data on such electromagnetic fields or experimental studies to indicate possible biological effects. There is considerable knowledge on the effects of electrical fields on fish in freshwater environments (e.g. Cowx and Lamarque 1990). Research into the strength, mitigation measures and potential biological impacts of such fields from undersea electricity cables is desirable to place this concern into context.

Mobile Sand Waves

In certain areas the seabed relief is not stable, and sand bank crests up to one metre high can move over time and thus bury or expose foundation sections and/or cables. They may also impose significant mechanical loading regimes on foundation structures. The presence of mobile sand waves at, or in the vicinity of, a proposed offshore wind farm site could therefore affect the design of foundation structures and undersea cable runs.

Scouring

Scouring of the seabed at the bases of offshore wind farm structures can be a serious issue with gravity caisson type foundations. The danger is that the scouring action can undermine the seabed beneath the caisson. Because gravity caissons (especially concrete) have larger diameters than piled structures, the local flow immediately around the caisson foundation accelerates to a higher speed, increasing the potential for scouring action compared with narrower, piled foundations. If there is a danger of scouring, a ring of protective armour (usually boulders) may be placed around the base. This action results in the formation of an artificial reef.

Scouring has not been reported as a significant issue with piled foundations, which have been used extensively in the offshore oil and gas sector. These foundations are typically driven 10 to 20 m into the seabed.

Alterations to Sea Currents

Offshore wind farm foundation diameters typically range from 4.5 m (piled) to 15 m (concrete caisson). Offshore, turbines are typically spaced at least 300 m from each other and can be more than 500 metres apart. The very low ratio of turbine foundation diameter to inter turbine spacing means that the effects on overall tidal current flows between turbines should be minimal.

Sedimentation

Changes to overall sedimentation patterns on the seabed between turbines seem unlikely due to the negligible effects on currents in these areas. However, sedimentation effects at the bases of individual structures may be significant. Such effects are likely to be highly site specific, i.e. dependent on local tidal flows, subsurface currents and seabed composition. The developers themselves will have to evaluate the implications of sedimentation on their foundation designs on a site by site basis.

3.3 Ecological Impacts of Offshore Wind Farms

There is only one report or publication on the environmental effects of offshore wind farms, largely reflecting their recent development (Percival 2000).

Guillemette *et al.* (1999) surveyed the abundance of eider ducks around an offshore Danish wind farm from 1994 to 1998. Results over the first three years suggested the ducks avoided the wind farm and the numbers declined since the wind farm construction. However, the 1997-98 survey results showed ducks did not avoid the wind farms, and indicated that duck abundance was closely related to the abundance of food, namely mussels. This experience demonstrated the importance of prior baseline surveys and of monitoring different components of the ecosystem, and the need for several years monitoring to understand year to year variation.

Seabed Habitat Impacts

The seabed provides a habitat for many species, and any constructions on the seabed will have a direct impact on some marine life. Some of these impacts can be considered beneficial if the new habitats created are suitable for species of commercial, recreational, or nature conservation importance. Particular functions of seabed habitats are to provide a place where young fish find refuge from predators, and where predators, such as larger fish and seabirds, find their food.

The most significant factor in protecting young fish from predation is the availability of three-dimensional habitat as is provided by rocks, seaweeds, sponges, hydroids and other marine life (Gregory and Anderson 1997, Thrush 1998). This habitat is reduced in complexity by bottom trawling (Auster and Langton 1999). However, the installation of concrete foundations may also reduce habitat complexity in the immediate area of construction through scouring, compacting and disturbance of the seabed.

During the breeding season, many coastal seabirds depend on small fish, such as sandeels and young fish of other species, as food for their chicks. While sandeels swim in large shoals near the sea surface, they also bury themselves in sand when not feeding. The role of habitats in potential wind farm sites as a source of food for sea birds thus needs to be considered in the siting and the design of foundations. Developers and environmental agencies must consider whether additional structures such as artificial reefs would be beneficial in that locality, either as a provider of habitat or barrier to bottom trawling.

Where alteration of existing habitats should be minimised, the ‘footprint’ of the construction works and final structures should be no greater than necessary. The completed structures will form a new habitat that will be rapidly colonised by marine life (this study, volume II). The design of these structures could be tailored to provide new habitats that select for certain species of fisheries or conservation importance.

Fishery Exclusion

The foundations of wind turbines will be obstacles to trawling. Other vessels will have to keep clear of the area to avoid collisions. A 500 m safety zone is typically established around such structures (e.g. Traves 1994), and effectively means that no trawling would be permitted between wind turbines. If angling is to be permitted within the area of a wind farm, then it may be necessary to provide moorings if anchoring is a risk to underwater cables.

Depending on the site selected, the immediate area occupied by wind farms may not be important for fisheries or may not occupy a significant proportion of the area normally fished. Those involved in fishing activities such as trawling, anchoring or the use of ground nets will also need to avoid electrical cables although these could be buried in the seabed where possible. Thus a greater area than the immediate footprint of the wind farm turbines themselves would be excluded from fisheries activities. In fact, some fisheries activities may need to be completely prohibited in the region of the wind farm and its associated subsea cables. Young fish are typically more abundant in shallow waters and where there is protection from predators. Important nursery areas do occur off the east coast of Ireland (e.g. Kelly, 1999, Connolly, personal communication). The increasing recognition by fishery managers of the need to have fishery exclusion areas to protect juvenile fish may complement the location of wind farms in these areas.

Seasonal Impacts of Construction

Some areas of seabed have particular importance during the breeding seasons of species, for example herring eggs are laid on the seabed over several weeks in different parts of the Irish coast (e.g. Molloy 1995). The time of spawning varies between different areas. It is possible that the construction activities will have a greater ecological impact than the completed structures. Consequently, if wind farms are to be developed in areas where such species spawn, then construction works should be conducted so as not to coincide with the spawning season.

Noise pollution, particularly from seismic surveys, may disturb wildlife. However, guidelines to avoid and minimise potential acoustic impacts have been developed by the UK Joint Nature Conservation Committee (Tasker, personal communication).

If the area is important as a feeding ground when seabirds are nesting, then construction work may need to avoid disturbance of feeding birds at critical periods in the breeding season. For these reasons, studies on the marine biotopes present at the site, on fish stocks of importance to fisheries and birds, and on bird and marine mammal activity, should be conducted prior to site development.

Other impacts

In addition to wind energy, fisheries, aquaculture and angling, other marine resources include sand and gravel aggregates, and oil, gas and coal resources. The extraction of these resources is unlikely to be permitted within the area of a wind farm. In this comparison, the wind farm would be a more environmentally benign impact than the extraction of seabed materials.

4. Positive and Negative Impacts of Offshore Wind Farms

In the wider environmental context wind farms have a positive impact as an alternative to the use of polluting fossil fuels for generating electricity. The scope of this study is limited to impacts on the underwater marine environment.

4.1 Concerns of Consultees

Most people and organisations consulted generally viewed offshore wind farms as having a positive environmental benefit because they provided a renewable source of energy and are seen as an alternative to more polluting fossil fuels.

Whilst most consultees recognised the benefits of sustainable energy from wind, they raised concerns regarding perceived negative impacts. This pointed to the apparent lack of benefits beyond those to the developers and to the state (in tax revenue) The issues raised during the consultation process are set out in Table 2 overleaf. This indicates a need for developers and the state to provide more information on the benefits of offshore wind farms to society, other marine resource users (especially fishermen), and to wild fauna and flora. Some consultees expressed a need for more detailed information in general, and specific information on individual developments, before they could formulate an opinion. This need for information is critical because most people and organisations will object to developments when information is lacking.

Consultees raised almost all of the possible impacts identified during this study. Two issues that were not raised were the possible impacts of trench construction for cable laying, and the use of blasting to remove boulders (which may not be necessary). There is considerable awareness of the sensitivity of the offshore marine environment. Indeed, during this study a new environmental group, Irish Offshore Coalition, was established (Table 1). This coalition will focus attention on the Irish offshore environment.

If developers or regulators fail to adequately account for the concerns of these and other groups, especially fishermen, it is likely that objections and legal challenges to wind farm developments will arise. Such situations are neither necessary nor desirable in the developer’s or public interest. This emphasises the need for making information available to the public, and of conducting Environmental Impact Assessments (EIAs).

The potential of wind farms as a location for artificial reefs and protected fishery areas were not identified by organisations consulted but, when raised, most consultees viewed these as benefits.

Critically, the Irish Fishermen’s Organisation and Bord Iascaigh Mhara predicted strong opposition from fishermen. They were not confident that potential benefits would accrue to fishermen from artificial reefs and/or fishery exclusion areas. Furthermore, the benefits from these practices may flow to different individuals than those whose activities were compromised. The question of mitigating impacts due to exclusion zones is one which will require careful consideration particularly with regard to the fishery sector.

Table 2. A summary of the main potential impacts of offshore wind farms raised during the consultation.

Concerns	Impact	Mitigation
Fisheries	• Loss of trawling ground	▪ Select sites of little or no value for trawling
	• Loss of areas for pot fishing	▪ Select areas of little or no value for pot fisheries ▪ Improve habitat for fishery species using artificial reefs
	• Damage to spawning grounds	▪ Avoid construction on spawning ground of species of commercial or conservation importance
	• Economic loss to fishermen with consequent social impacts	▪ Quantify value of existing fisheries and community affected before development ▪ Develop measures to directly or indirectly compensate fishermen for economic loss
Electro-magnetic fields	• Impact on natural fauna and flora, especially fisheries	▪ Shield and bury electrical cables
Acoustic surveys	• Seismic survey impacts on marine fish and mammals	▪ Follow JNCC guidelines ▪ Assess whether necessary ▪ Minimise duration and area affected
	• Underwater transmission of sound from turbines in operation	▪ Develop methods to reduce and monitor
	• Disturbance to marine life (birds, mammals, etc.) during construction	▪ Minimise duration and area affected
Hydro-graphy	• Scouring, erosion and sedimentation on seabed	▪ Design foundations to minimise scouring, erosion and sediment redistribution
	• Altered current flows	▪ Design foundations and 'footprint' of area affected to minimise alteration to water flow
Navigation	• Routine traffic to wind farm	▪ Management plan to minimise need to visit wind farm ▪ Develop technology for remote monitoring of wind farms and adjacent area (e.g. video)
	• Need to alter existing sea traffic routes	▪ Avoid construction near main navigation routes
	• Increased risk collisions	▪ Select sites and traffic routes to minimize risk of collisions
Waste disposal	• Waste generated during construction and maintenance may litter seabed	▪ Develop auditable procedures to verify return of waste to shore for authorised disposal
	• Removal of installations	▪ Plan for removal of foundations and turbines
	• Artificial reef may be used as location for solid waste disposal	▪ Strict regulatory control and definition of what materials may be used as rock armoring and

Concerns	Impact	Mitigation
		artificial reefs
Visual	• Perceived negative impact of sea views	▪ Design to reduce visibility at a distance, while not compromising need for all types of shipping to be able to avoid windmills in all weather conditions
General	• encourage and extend precedent for the sea to be regarded as a convenient alternative for operations unacceptable on land	▪ Strict regulatory control, monitoring and enforcement ▪ Equal consideration by regulators of needs of existing users, environmental organisations, general public, and developers
Birds	• Changes to seabed or benthos may alter food supply	▪ Identify bird usage of potential sites and select sites and structure design to maintain or improve habitats for species of importance to birds
	• Collision with blades	▪ Do not site in main bird flight path (e.g. between feeding and nesting area)
	• Disturbance by construction, operating noise, and traffic	▪ Design construction and operating procedures with knowledge of bird use of the area, so as to minimise negative impacts
Sea mammals	• Disturbance to whales and dolphins by seismic surveys, construction, and operating noise	▪ Prior assessment of the use by sea mammals of proposed sites ▪ Review need for seismic surveys ▪ Minimise duration and quantity of noise during construction ▪ Quantify, minimise and monitor underwater noise levels during operation
Seabed life	• Footprint of turbine foundations and cables, traffic, electromagnetic radiation, noise may reduce abundance and diversity of seabed life (benthos)	▪ Detailed map of benthos prior to development ▪ Design of wind farm to maintain or improve habitats for species of commercial and conservation importance ▪ Stock area with shellfish (e.g. lobster, scallop, oyster) to develop resource

4.2 Mitigation

Statutory Approval

It is envisaged that the Department of the Marine and Natural Resources will issue licences for offshore wind farms in two phases. In the first phase a developer would be given permission for an initial investigation which will determine the suitability of the site. Once suitability is established, a detailed Environmental Impact Statement will be conducted which will be submitted with an application for an operating licence. The EIS requires detailed descriptions of the project, descriptions of the existing environment in the project area, archaeology, effects of the project during construction, operation and decommissioning, the alternatives considered, mitigation measures and monitoring programmes.

Information on proposed wind farm operating procedures will be required, including monitoring to confirm compliance with licence conditions and predictions in the EIS. This may include monitoring of underwater noise and electromagnetic fields, and of changes in fish stocks, birds, mammals, and other marine life. Other activities to be monitored would include the use of the area by fishermen, anglers, scuba divers, and others, whether such activities are permitted or not. A video surveillance system may assist monitoring of human activity, mammals and bird activity around the wind farm.

In preparing the EIS and planning the development, a range of methods to avoid or reduce possible negative impacts should be considered, as well as seeking to increase the likelihood of positive impacts. Examples of mitigation measures are outlined in Table 2. Some of the possible negative impacts may not arise in certain locations or based on certain designs. For example, a typical monopile construction of 5 m diameter has a footprint of up to 20 m^2 and does not result in significant scouring or alteration to water flow beyond a few metres. In some locations fishing, bird and/or mammal activity may not be significant. However, all these issues must be addressed within the EIS and then considered within the EIA by the regulatory authority.

Use of Marine Protected Areas

An increasing number of studies have examined the effects of excluding or greatly reducing fishing in defined marine protected areas (MPA). The primary effect of fisheries is to reduce the abundance of the larger fish in selected populations. Thus most of the studies find an increase in the number of larger fish in MPA (e.g. Alcala 1988, Garcia-Rubies & Zabala 1990, Francour 1991, Rakitin & Kramer 1996, Russ & Alcala 1996, Chapman & Kramer 1999, Nowlis & Roberts 1998). An increase in the number of fish species, fish abundance, fish biomass, and the number of smaller fish, are also common benefits of MPA. Where data is available, fishermen report greater catches near MPAs (e.g. Russ and Alcala 1996).

Most of the studies confirming the benefits of MPAs to fisheries have been mainly conducted in tropical and sub-tropical seas, such as Mediterranean (Garcia-Rubies and Zabala 1990, Sasal *et al.* 1996, Francour 1991), Caribbean (Rakitin and Kramer 1996, Roberts and Hawkins 1997), Philippines (e.g. Russ and Alcala 1996), and New Caledonia (Wantiez *et al.* 1997). However, the benefits of areas closed to fisheries similarly apply to north-eastern Atlantic waters (Horwood *et al.* 1998). In the UK, fishery exclusion zones around oil and gas platforms are reported to "have become havens for fish and shellfish" (Traves 1994). The benefits will depend on fish species, fish sizes, the duration of the fishery closure, and the relative intensity of fishing pressure outside the MPA (e.g. Horwood *et al.* 1998, Nowlis and Roberts 1998).

For a given species, larger fish produce significantly more eggs and thus contribute more to population growth than an equivalent number or biomass of smaller fish. Thus the larger fish living in MPAs can contribute significantly to the production of young fish which will disperse outside the MPAs. Nowlis and Roberts (1998) modeled the potential of MPAs to contribute to commercial fisheries. They found that the contribution depended significantly on the size of the MPA, and that a typical effect was to reduce annual catch variation. Thus, the larger the area of MPA relative to the fished area, the greater would be the benefits to the fishery. However, even small MPAs can improve fish stocks; fish biomass doubled in one 2.6 ha reserve over 2 year period (Roberts and Hawkins 1997). Analysis of fish home ranges concluded that the larger the MPA the greater number of species of fish whose populations could be protected (Kramer and Chapman 1999). While it would be difficult to detect a commercial benefit from small MPAs, Nowlis and Roberts (1998) concluded that MPAs were a viable fisheries management option and especially beneficial for species with slow population growth rates.

Attempts to control over-fishing through size limits and quotas have proven difficult to manage, and often result in significant mortality of 'by-catch'. It can also be more difficult to enforce partial fishery controls than simple bans. There is a strong argument that a network of MPAs may be an essential tool for ensuring the sustainability of fish stocks and the only option for protecting and restoring marine food webs (Roberts 1997, Pauly *et al*. 1998). Indeed, regardless of the development of offshore wind farms, the development of MPAs may occur to protect fisheries, and is likely to happen in response to the EU Habitats Directive.

Some types of fishing, notably bottom trawling, and dredging damage the seabed and its marine life (e.g. Jones 1992, Kaiser & Spencer 1996, Macdonald *et al*. 1996, Collie & Escanero 1997, Lindeboom & de Groot 1998, Freese & Auster 1999, Prena *et al*. 1999). The consequences of these impacts for fisheries are the subject of considerable research at present. Certainly there are negative impacts on seabed biodiversity, and nature conservation management seeks to protect some areas from trawling and dredging for this reason. Thus it is probable that at least trawling and dredging will be prohibited within marine MPAs designated as Special Areas of Conservation under the EU Habitats Directive.

The establishment of MPAs can provide opportunities to enhance shellfish stocks that would otherwise be damaged by trawling and dredging. The stocked animals can be managed to provide a valuable and predictable harvest, and their natural spawning will contribute to populations outside the MPA. One of the best examples of an MPA in an Irish context is in Mulroy Bay. The scallop population in the North Water of Mulroy Bay, in north-west Ireland, has been supplemented by hatchery reared seed, and has the highest production of scallop spat in Ireland, and perhaps Europe. Dredging has been prohibited in the area to protect the scallops and their habitat. The collected spat are used in aquaculture outside the bay and some are exported overseas.

Natural Reefs in Ireland

In Irish waters, natural reefs are comprised of boulders, bedrock and cliffs, with coral reefs in deeper waters off the west coast. Natural reefs in Irish waters support a diverse fauna and flora, including species of commercial, recreational and nature conservation importance (Picton and Costello, 1998). Shipwrecks, breakwaters and other manmade structures develop a similar fouling community to that on natural "hard" substrata such as boulders and cliffs in Ireland (authors, personal observation) and overseas (e.g. Matthews 1985, Ambrose & Swarbrick, 1989). The fauna and flora of both natural and artificial reefs are similar in structure, comprising sessile species forming a covering over the surface, crevice living species, and species that move over and swim around the structures. Artificial reefs in Ireland would be colonised by these communities with the exact species compositional abundance depending on local environmental conditions, including the reef design.

Reefs are a habitat for which nature conservation is required in Europe under the Habitats Directive (Council of the European Communities 1992). However, rocky reefs are widespread in Ireland, especially on the west coast. The creation of artificial reefs may thus add to this habitat. Other habitats are also legally protected, notably maerl beds (calcareous granules formed by a marine alga). Some maerl beds are also of commercial importance. However, maerl beds are not widespread and careful selection of wind farm sites would avoid impacting these habitats.

Potential of Wind Farms as a Location for Artificial Reefs

Artificial reefs may form part of a wind farm design. They may result from the placement of a gravity caisson concrete foundation and/or the addition of rock armour around the base of the foundation. There is considerable evidence that such reefs can provide benefits to fisheries, including angling (this study, volume II).

Artificial reefs are "submerged structures deliberately placed on the seabed to mimic some characteristics of a natural reef" (see Supplementary Report Volume II for full review of literature and references). They are a well-established tool for fisheries management, nature conservation, and coastal zone management in many countries of the world. Specially designed and constructed steel and concrete reefs have been used to modify about 10% of the Japanese coastline to enhance fisheries. In the USA reefs made from waste materials have been used, notably off Florida, primarily to enhance recreational angling. In Europe, artificial reefs have been deployed for about 30 years with a variety of objectives. Activity is focused in southern Europe, with Italy, France, Spain and Portugal all deploying reefs along sections of their coast. In Northern Europe artificial reefs are in place in Finland, The Netherlands, and UK. They have been on an experimental rather than commercial scale. Deployment is on a much smaller scale than seen in Japan. The dominant material used is concrete. In all countries artificial reefs have been government funded.

Traditionally, artificial reefs have been constructed for fishery enhancement, but they are now built to serve a number of purposes in coastal zone management such as:

- Improvement of fishing catches and quality;
- Provision of spawning areas, and to protect juvenile and broodstock habitats;
- Preventing trawlers from using certain areas;
- Shellfish and finfish ranching to protect and supplement natural stocks;
- Recreational angling;
- Shore protection and control of beach erosion;
- Breakwaters;
- Mitigation and restoration of degraded habitats;
- Providing amenable scuba diving sites in sheltered areas;
- Waste disposal options;
- Scientific experiments;
- Recycling of nutrients in areas where bivalves (molluscs) are farmed;
- Resolving potential conflicts between user groups of the marine resource;
- Recreational surfing.

Promotion of Fisheries and Recreational Angling

Reef deployment has increased fishery yield at a local scale. An additional benefit of excluding trawlers from shallow water has been to encourage local artisan fishermen and provide income for local communities. These fishery management initiatives can pose difficulties in policing the fisheries, but these difficulties exist outside reef areas as well.

Promotion of Aquaculture

In the Adriatic Sea reef units are used as anchors for suspended cultivation of growth of mussels, and European and Pacific oysters. The increased structural complexity provided by the long-lines provides additional niche opportunity for fish and so both wild fishery and aquaculture can flourish. The reef design was progressively developed and is now in commercial application at four Adriatic sites. Mussel harvesting is the main application and yields of 20-55 $kg.m^{-2}$ have been recorded. Average income from a reef site is estimated at US$258,000, allowing reef deployment costs to be recovered in about five years.

Nature Conservation

The first reefs deployed in Europe, off Monaco in the 1960s, were placed to provide habitat for marine life and so promote nature conservation. This work has continued in the development of artificial cave habitats for the over-exploited red coral. Developments of marine parks and marine reserves in other areas of the Mediterranean have used artificial reefs to effectively prohibit trawling as well as adding habitat diversity, which usually increases species diversity. Spain currently has 9 marine nature reserves. In most of these marine reserves some kind of artificial reef has been placed to protect the seabed from trawling.

Suitability of Waste Materials in Artificial Reef Construction

Both Italian and UK projects have tested cement stabilised pulverised fuel ash (waste from coal fired power stations) extensively and shown it to be non-toxic and a suitable material for construction and colonisation by sea life. This success and development of test protocols has encouraged interest in the assessment of tyres and stabilised quarry slurry and harbour mud as reef materials.

Research into Reef Life

Most artificial reefs have been studied to provide a description of the colonisation process. The development of both sessile and mobile fauna dominates these types of studies. Comparison shows the expected differences between temperate and Mediterranean conditions and oligotrophic and eutrophic waters. Colonisation in temperate and eutrophic waters seems to stabilise after about five years whilst oligotrophic communities may still be developing ten years after immersion. Diver observation and tagging together with telemetry have improved the knowledge of how some species exploit reef spaces. Further research to understand the optimal reef design for different species is required.

Breakwaters

The 'artificial reef function' of a breakwater would be secondary to its primary purpose. However, breakwaters are typically located in sediment dominated areas and may provide the only reef habitat in the area. The provision of hard habitat in coastal waters opens up opportunities for increasing habitat and species biodiversity, new commercial fishery exploitation, recreational uses for angling and scuba diving, as well as 'offshore' suspended, cage and bottom aquaculture.

Whatever the final choice of secondary function the selection process must involve extensive stakeholder dialogue. The chosen site must be fully assessed before structures are proposed so the secondary benefit can be maximised and all the implications of deployment may be recognised.

In addition to these benefits identified in the literature review artificial reefs may also provide a protected location for environmental monitoring equipment. In the UK, the Crown Estate will reserve the right to use wind measurement data collected at proposed wind farm sites for generic other purposes (Jacobson 2000). The most likely foundation for wind turbines in Ireland is likely to be mono or multiple pile structures (Section 3.2.1 this report), and these will require little to no rock armouring. However, the electrical cables may require covering in rocks to protect them from trawling. It is likely that benefits to fisheries will arise from the exclusion of bottom trawling in the wind farm area, regardless of the presence of artificial reefs. Artificial reefs would provide most benefit where similar natural reefs were scarce. While the construction of artificial reefs in association with wind farms is probably not necessary to provide fishery benefits, such reefs may provide protection against illegal trawling.

Commercial Species on Reefs

Several species of commercial importance to the Irish economy are associated with reefs. These may:

- Live within reefs, notably lobsters, shrimp, crabs and crawfish;
- Grow attached to reefs, such as mussels or native oysters;
- Swim around reefs, such as cod, saithe, and mackerel;

- Live on seabed sediments around reefs.

Thus reefs are directly important as a habitat to some commercial species (Table 3). They can also act as barriers to trawling over sediments where other commercial species live. The present annual value of fisheries associated with natural reefs is estimated at over IR£60 million (Euro 76 million)(Table 3).

Reefs for Angling

Existing examples of artificial 'reefs' in Ireland include breakwaters, shipwrecks, and other coastal structures. These structures provide some of the most popular locations for land-based sea angling. One reason natural and artificial reefs are popular with anglers is that fish congregate around the reefs. For these reasons, the Beara Tourism Development Association in south-west Ireland has funded a study to assess the feasibitity of improving sea angling through the use of artificial reefs.

Trawling is difficult around reefs and the reefs may act as a habitat for juvenile (a 'nursery') and adult (a 'broodstock' habitat) fish. Most species of importance for recreational angling are associated with natural reefs (Table 4). Others species of angling importance, such as flounder, plaice, ray, skate, turbot, angler fish (monkfish), dab, gurnard, sole, live on sediments around reefs. There are regional differences in the sea angling community (Central Fisheries Board, personal communication). Some 50 to 60 private angling boats operate from the east coast of Ireland compared with only 4 charter boats. In contrast, most boats on the south and west coasts are for tourist charters. These numbers of boats indicate the considerable social and economic importance of sea angling in Ireland. About 90,000 people participated in sea angling in 1996, and spent an estimated £9 million per annum (ESRI 1997).

Nature Conservation

Few marine species have been identified as being important for nature conservation in Ireland, largely reflecting the limitations of available information. The habitat-forming plants, seagrass and maerl are protected under the Habitats Directive but do not occur on reefs. Some fish species of nature conservation interest in Ireland, although not legally protected, are reef living. For example, the red-mouth goby only occurs on rocky cliffs in Lough Hyne in south-west Ireland, and Couch's goby only occurs amongst rocks in shallow-water in three localities in Ireland: Lough Hyne, Bantry Bay and Mulroy Bay.

Rocky and reef habitats are the least studied marine seabed habitats in European waters because of the difficulty in sampling them. The BioMar-LIFE survey of almost 900 sites in Irish waters found that they harbour a greater number of species and biotopes than sediment biotopes (authors, unpublished data analyses). Artificial reefs would provide additional habitat for these species. While particular species living on reefs have not yet been singled out for protection, by protecting examples of natural reefs, Ireland would be fulfilling some of its obligations under the EU Habitats Directive, and its requirement to designate Marine Protected Areas under the Convention on Biological Diversity.

While the present study does not address above-water environmental impacts such as on bird flight paths (Percival 2000), birds may use wind farm areas for feeding and resting. Impacts will be species and locality dependant, such that caution is required in extrapolating from studies in other areas. However, present studies indicate wind farms have no significant impact on bird life (Percival 2000). A standard methodology for assessing wind farm effects on birds is being developed (Percival 2000).

Table 3. Species of commercial importance that are associated with natural reefs in Ireland, and may be expected to inhabit artificial reefs. Latin names of species are in Annex 1.

Shellfish		*** Value to economy IR£1,000's**
Crustaceans	Lobster	4,465
	Shrimp	1,652
	Edible crab	5,606
	Velvet (swimming) crab	495
	Crawfish (crayfish)	658
	Spider crab	143
Molluscs	Mussel **	1,800
	Octopus	14
Fish	Cod (incl. roe and codling)	6,439
	Saithe (coalfish)	1,013
	Haddock	4,825
	Mackerel	18,335
	Conger eel	94
	John dory	265
	Ling	845
	Monkfish (anglerfish, incl. tails)	7,048
	Mullet	49
	Pouting	5
	Spotted dogfish	239
	Spur dogfish	833
	Whiting	5,803
	Other demersal	129
TOTAL		**60,755**

* From Bord Iascaigh Mhara (1999). ** some live on seabed sediments.

Table 4. List of species of importance for recreational angling in Ireland which are associated with natural rocky reefs and shipwrecks, and may be expected to associate with artificial reefs.

Species	**Species**	**Species**
Ballan wrasse	Cod	Mackerel
Cuckoo wrasse	Saithe (coalfish)	Bass
John dory	Pollack	Grey mullet
Conger eel	Pouting	Sea trout
Spur dogfish	Whiting	
Greater spotted dogfish	Ling	Three bearded rockling

5. Guidelines and Protocols for Offshore Wind Farms

In this section we set out a list of issues to be addressed in preparing an EIS for offshore wind farms. We have received from the Department of Marine and Natural Resources a draft contents list for EISs for offshore wind farms. We have reviewed same. The following suggestions would, we believe, enhance the evaluation of the undersea environmental impacts.

5.1 Foundation Design

A key factor influencing the impact on the marine environment "below the sea" is the foundation type. The selection and design of foundations is highly specific to the site location. Therefore, it should be left to developers to select and justify the best design for individual locations. Developers should consider whether a particular type of foundation may perform better than others in terms of environmental impact. The suitability or otherwise of a particular foundation design for the purposes of creation of artificial reefs should be addressed by the developer in the EIS.

5.2 Mobile Sand Waves

In the shallow waters of the banks off the east coast where most interest in wind farms is currently directed, a physical phenomenon is the occurrence of mobile sand waves. The attention of developers should be drawn to the existence of these sand waves, which may have implications for foundation design and undersea cable location.

5.3 Debris from Construction and Maintenance Activities

A concern expressed in the literature and through the consultation process is the risk that construction and/or maintenance debris from the operation of wind farms will pollute the seabed. It should be a condition of a licence and lease that the leaseholder is responsible for keeping the seabed inside the leased area free of debris. This will involve a degree of monitoring by the operators.

5.4 Artificial Reefs

In suitable areas, the provision of artificial reefs could be considered as a means of marine resource development in the vicinity of a wind farm irrespective of foundation type. Monopiles will not require rock armour protection and consequently will not form an artificial reef. Assuming that there are suitable water and seabed conditions at the site, developers may propose artificial reefs. Where artificial reefs are proposed the water depth, zone of wave action, sand waves and the draught of various vessels are all issues that must be addressed in the EIS. However, there is no reason to choose wind farms over any other areas for locating artificial reefs.

5.5 Biological Impacts

The EIS should determine the significance of the wind farm development to marine life, including species of importance for commercial and recreational fishing and nature conservation.

The EIS for an offshore wind farm should include:

- A map of seabed biotopes;
- An assessment of sediment types;
- Assessment of commercial fish population structure;
- Assessment of sea angling resource;
- Activity of sea birds and mammals in the area which may be affected by the wind farm, defined as either a fishery exclusion area or restricted navigation zone (whichever is the greater).

These studies should be in sufficient detail to:

- Quantify value of fishery species resources;
- Quantify angling resources;
- Identify biotopes and species of nature conservation importance;
- Determine if, when and how sea birds and mammals depend on the area for their livelihood.

This information should be used to propose mitigating and compensatory measures if necessary.

5.6 Monitoring

The EIS should include a design for a monitoring programme to confirm the predictions of the EIS in terms of environmental impacts.

5.7 Decomissioning

The EIS should provide plans for the eventual decommissioning of the generating station and the clearance of the site.

5.8 Alternative Uses for Sites

The EIS should include an evaluation of the opportunity costs associated with alternative uses for the proposed offshore wind farm site. Such uses could include:

- Oil and gas exploration;
- Coal extraction;
- Gravel extraction.

6. Recommendations for Research & Development

6.1 Shallow Water Banks

Using current technologies, economics constrain the development of offshore wind farms to water depths of 10 to 15 metres. The thrust of future research programmes in the field of offshore wind farms should focus initially on issues of interest in these depths, particularly on the east coast. Desk and field research should be initiated on:

- The ecology of the offshore banks with particular reference to species of economic and ecological importance;
- The dynamics of shallow banks on the east coast of Ireland.

However, as technology improves, and opportunities for developing wind farms in greater water depths emerge, the R&D programme can be expanded accordingly.

6.2 Foundation Designs

Because of their importance in physical environmental impact terms, there should be a library research programme to keep abreast of developments on offshore wind turbine foundations on an ongoing basis. This may involve setting up special library section to facilitate retrieval of references on the subject. The task should be assigned to a nominated agency or, alternatively, it could be undertaken by placing a contract externally for such an updating service.

6.3 Fisheries

The Department or its agencies should begin studies on the value of the fishing industry and other beneficial uses in the sea areas of most interest to wind farm developers. The impact on fisheries (both positive and negative) should be calculated and the revenue from the power generated established. This background data is required for the purposes of discussions on the areas of leases, access, impacts and possible compensation.

6.4 Undersea Cables

The Department or its agencies should conduct a desk and field research programme on the effects of cables on marine flora and fauna. The research should include experience from existing Danish and Swedish wind farms and any projects built in the next 5 years. Field research on the impact of existing electricity cables in Irish waters would add to the knowledge of potential impacts.

6.5 Artificial Reefs

Some field trials on the impact of artificial reefs under Irish conditions should be initiated. The objective would be to position reefs at different locations, using different media and observe the impact of the pilot reefs on habitats. There is no particular need to couple this research with wind farm development.

6.6 International Research

Investigate possibilities for joint research programmes with agencies in Denmark, Sweden, Netherlands and UK who may also be interested in the topics above, including the availability of EU funding for such research. Topics for joint research might include electromagnetic effects, vibrations, and corrosion protection.

6.7 Demonstration Projects

Demonstration projects are urgently required to determine the costs and benefits of fishery exclusion areas to:

- Species of fishery and angling importance;
- Social aspects of fishery communities;
- Economic conditions of fishery communities;
- And impacts on other marine life.

These projects will provide facts and experience in an Irish context to identify whether, when and where fishery protected areas may have direct and indirect benefits to Irish fisheries. This is relevant to wind farms and to wider fishery management and nature conservation.

6.8 Coastal Zone Management

The planning, management and communication of information to the public and other coastal users would be assisted if all relevant environmental data was collated and updated with a marine and coastal Geographical Information System. This should integrate information of interest to different government offices and ideally would make it accessible via the world wide web.

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Annex 1: Common and Latin Names of the Species Mentioned in this Report.

Common	Latin
CRUSTACEA	
Crawfish (marine crayfish)	*Palinurus elephas*
Edible crab	*Cancer pagurus*
Lobster	*Homarus gammarus*
Prawn (Dublin Bay prawn)	*Nephrops norvegicus*
Salmon (Atlantic salmon)	*Salmo salar*
Shrimp	*Palaemon serratus*
Spider crab	*Maja squinado*
Velvet (swimming) crab	*Necora puber*
MOLLUSCA	
Mussel	*Mytilus edulis*
Octopus	*Octopus vulgaris, Eledone cirrhosa*
PISCES	
Angler fish (monkfish)	*Lophius piscatorius*
Bass	*Dicentrarchus labrax*
Ballan wrasse	*Labrus bergylta*
Cod	*Gadus morhua*
Conger eel	*Conger conger*
Couch’s goby	*Gobius couchi*
Cuckoo wrasse	*Labrus mixtus*
Grey mullet	*Chelon labrosus*
Haddock	*Melanogrammus aeglefinus*
John dory	*Zeus faber*
Greater spotted dogfish	*Scyliorhinus stellaris*
Lesser spotted dogfish	*Scyliorhinus canicula*
Ling	*Molva molva*
Mackerel	*Scomber scombrus*
Pollack	*Pollachius pollachius*
Pouting	*Trisopterus luscus*
Red-mouth goby	*Gobius cruentatus*
Saithe (coal fish)	*Pollachius virens*
Sea trout	*Salmo trutta*
Spur dogfish	*Squalus acanthias*
Three bearded rockling	*Gaidropsarus vulgaris*
Tope	*Galeorhinus galeus*
Whiting	*Merlangius merlangus*

Annex 2: Areas prohibited by Department of the Marine and Natural Resources for Use as Offshore Generating Stations/Structures

Areas of navigational importance:

- the traffic lanes off the Tuskar Rock Traffic Separation Scheme and areas extending from the termination of these lanes;
- the traffic lanes off the Fastnet Rock Traffic Separation Scheme and areas extending from the termination of these lanes;
- areas where dedicated anchorages are being used.

Certain areas used by the Department of Defence as gunnery, bombing or firing ranges are also unavailable. These are:

- Sea/coastal area SSW of Cork - the area within straight lines joining the points 513412N 084236W, 512012N 083436W, 511736N 084848W, 513142N 085706W, 513412N 084236W.
- Gormanstown - area contained within a circle having a radius of 3 NM centred on 533841N 061343W, with an additional area contained within the smaller segment of a circle of radius 10 NM centred on 533841N 061343W and radial boundaries on the true bearings 015° and 106°.
- Cork Harbour - area contained within straight lines joining the following points: 514700N 081000W, 514630N 080000W, 513830N 081500W, 514400N 081900W.

Enquiries relating to any possible changes to these defence areas or derogations from the prohibition should be made to The Executive Branch, Department of Defence, Infirmary Road, Dublin 7 (Telephone +353 (0) 1 8042000) (Department of the Marine and Natural Resources, personal communication, February 2000).

Annex 3: Current Knowledge on the Environment of the Irish Sea Coast of the Republic of Ireland

There are recent useful reviews of the marine environment of the east coast of Ireland in Nairn *et al.* (1995) and the Marine Institute (1999). This report briefly summarises current knowledge and indicates sources of more recent information.

Physical environment

In general the Irish Sea is shallow (most < 100 m), exposed to strong tidal currents (up to 1.2 m s^{-1} or 3 knots), has a narrow annual temperature range (7-14 ^{o}C), and a seabed of gravel and sand (Lee and Ramster 1981). The almost linear appearance of the east coast of Ireland in comparison to the west coast may suggest an area of limited physical variation. However, the few headlands, islands, and subtidal rock outcrops (e.g. Codling Bank), combine with the tidal currents to create areas of different water movement and velocity, sediment types, shallow banks and deep holes. The latter include the Lambay Deep (140 m depth) and the Codling Deep (120 m depth) (Admiralty Chart No. 1468). The origin of these Deeps is enigmatic and of geological interest (Merne *et al.* 1990). The very strong water currents in the deepest parts of the Codling Deep may create sufficient scour to prevent sediment accumulating in the Deep (authors, personal observations). These currents are probably responsible for the well-sorted gravel and shell in both the Codling Deep and the adjacent Kish and Codling Banks (authors personal observation). The strong tidal currents reflect the forcing of Celtic Sea waters into the narrower Irish Sea by tides and wind (Lee and Ramster 1981). The seabed is composed almost entirely of sediments of glacial origin ranging from small boulders and stones in areas exposed to strong currents (e.g. area off Wicklow coast), to fine muddy sands in deeper areas less exposed to currents (e.g. Lambay Deep).

Oceanography

The strong currents result in most of the Irish Sea being well mixed vertically, and commonly having high levels of suspended matter in the water (authors, personal observations). The high turbidity limits plant growth, and benthic algae are rare below 10 m depth (authors, unpublished data). The area between north County Dublin, Carlingford Lough and the Isle of Man does become stratified during the summer, and phytoplankton production may thus be expected to be greater there (Raine *et al.* 1993). Plankton abundance in the Irish Sea is less than half that in other Irish waters (Brander *et al.* 1987). While the limited penetration of light, and largely sedimentary seabed may exclude certain benthic algae from the Irish Sea these are not reasons to expect benthic fauna to be any less diverse than on other coasts. Indeed, the strong currents may aid species dispersal, and the large areas of subtidal sediments in particular may result in greater richness of infaunal species than may be found on other Irish coasts.

The surface temperature of the Irish Sea is 1 - 2 ^{0}C cooler than other Irish coasts in winter and summer (Lee and Ramster 1981). While the bottom temperature is similarly cooler in winter it is 1 - 2 ^{0}C warmer than bottom waters on other Irish coasts in summer. These contrasting temperature conditions probably reflect the absence of deeper waters to stabilise temperature and the limited area of stratified water in summer in the Irish Sea. Such differences may significantly affect the distribution of species.

Ecology

In reviews of publications on the fauna and flora of the Irish Sea, Merne *et al.* (1990) and Mackie (1990) found the majority of papers concerned observations on a few species from a few locations. Brander *et al.* (1987) and Mackie (1990) provided maps of communities that were expected to occur in the Irish Sea but these were largely predictions based on very limited field data. Additionally, such broad predictions could not reflect the real diversity of the marine communities. However, a few papers, notably that of Massy (1912), had surveyed a wide range of species and more studies have been conducted since these reviews (Erwin *et al.* 1990, Mackie *et al.* 1995, Hensley 1996, Fox *et al.* 1996, authors unpublished data).

Sampling of seabed fauna and flora in the western Irish Sea has identified benthic communities on sands in the south-west (Keegan *et al.* 1987), muddy sands, sands and rock in Dundrum Bay (Erwin *et al.* 1987), fine sands in Dublin Bay (Walker and Rees 1980, Benthos Research Group 1992), rock, sand and mud in Carlingford Lough (Erwin *et al*. 1990), deep water mud in the north-west (Hensley 1996, Fox *et al*. 1996), and sandy mud and gravel in the mid-west (EcoServe, unpublished data) Irish Sea. In most cases the authors were able to group species together and link these groups with certain seabed substrata and/or depth.

From available studies, it is possible to identify six seabed regions in the Irish Sea (Figure 1). The seabed is almost entirely sediment, ranging from muds (Regions 1-3) through to sand, shell, gravel and cobbles to stones and small boulders. Rocky habitats (Region 6 d) are largely confined to the intertidal and shallow subtidal, but commonly occur below 25 m around the Saltees Islands to Hook Head area. Epifaunal species are widespread throughout the region, and characterise gravel, cobble, boulder and rocky habitats. Infauna is more important in areas with sand and mud. The habitats and biotopes within these regions could be described in more detail where more sampling stations occur (Figure 1).

Detailed studies of the benthos of the south-eastern (Mackie *et al*. 1995) and south-western (Keegan *et al*. 1987) Irish Sea found the faunal assemblages to be poorly related to others described for the English Channel and French coast. The apparent failure of these studies to identify consistent and distinctive biotopes probably reflects different sampling methods, different methods of assessing dominant species (e.g. abundance, frequency of occurrence, conspicuousness), and natural seasonal and annual variation in species abundances (e.g. due to storms, temperature, predation, disease, etc.). In contrast to the above studies, Swift (1993) found distinct groupings of species in repeated surveys of sediments in the eastern Irish Sea, and that their characterising species were similar. Reanalysis of data in other Irish Sea studies that takes the differences in methods into account, and using a standard analytical approach, may reveal that either they are more similar than initially apparent, or that distinct infaunal communities do not occur. The BioMar project has developed a system for classifying marine biotopes in Ireland and Britain (Costello 1995, Picton and Costello 1998), and a classification has been published (Connor *et al.* 1997a, 1997b). This methodology and classification is being used by the SensMap (Seabed Sensitivity Mapping) INTERREG project to map seashore and inshore biotopes in the southern Irish Sea (Emblow *et al.* 1999).

Temporal Variation and Human Impacts

Marine biotopes may change over time. Detailed multivariate analyses of benthic surveys of Dublin Bay in 1971 and 1989 identified groups of species but with different characteristic species. These differences may be an accurate reflection of temporal change, particularly of the sand mason *Lanice conchilega*, to which several other abundant and characterising species were attached (Benthos Research Group 1992). These changes are likely to have been influenced by the nutrient enrichment of the estuary (Jeffrey *et al.* 1993, 1995).

The effects of fishing, nutrient inputs to estuaries, and other pollutants (e.g. TBT) may be important in altering the natural community structure. It is also possible that sediment dwelling species live in a wide range of sediment types but that their abundance (rather than occurrence) varies according to both the above factors and sediment preferences. The high level of trawling and other fishing in the Irish Sea (Brander *et al.* 1987) has probably affected benthic communities directly through physical disturbance of the seabed, and indirectly through altering the abundance of fish and other species in the ecosystem. Most of the area has been trawled since 1890 (Holt 1910), and no information on the pre-trawling state of the fauna exists. The lack of a difference in communities between control and trawled areas in the north-western Irish Sea suggested that both areas had already been affected by trawling (Fox *et al.* 1996). Massy (1912) found the burrowing urchin *Brissopsis lyrifera* to dominate her trawl samples. However, this species, known to be sensitive to trawl damage, was not found by Fox *et al.* (1996). While the magnitude and ecological significance of these effects are not clear, recent surveys cannot assume they are describing natural communities.

Current Studies

Several projects funded under the Wales-Ireland INTERREG programme are producing information that will fill gaps in published knowledge. In particular, the SensMap project has mapped the habitats and biotopes of the seashore and inshore seabed of counties Dublin, Wicklow and Wexford (Emblow *et al.* 1999). Further offshore the SWISS (South-West Irish Sea Survey) project has collected biological information from sampling stations. These projects are presently being completed and further information is available on them from Ecological Consultancy Services Ltd (*EcoServe*) for SensMap and Dr J. Wilson, Trinity College Dublin for SWISS. A third project, the Irish Sea Hydrodynamic Modelling Network, is reviewing existing hydrographic models in the Irish Sea. Other projects concern roseate terns, seals, cetaceans, and aspects of oceanography (see web site http://www.marine.ie/intcoop/interreg/ for more information).

The combination of published information and the INTERREG projects will provide a broad overview of the seabed environment in the southern Irish Sea. This will enable the conditions at particular locations, for example where a wind farm may be proposed, to be put into a wider context. It is likely that the density of current sampling stations would result in few samples having being collected in a particular location. Similarly, while some hydrographic models may characterise general current conditions in an area, it would be recommended that site specific measurements (and perhaps models) be obtained. Thus new field surveys would be essential to characterise the environmental conditions and biotopes for an Environmental Impact Statement.

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Figure 1. Seabed regions within the western Irish Sea. Region boundaries are indicative as the seabed and associated fauna shows a gradual transition between areas. The red dots indicate the sites where information on seabed life is available. They are drawn from data contained in the publications of Walker and Rees (1980), Keegan *et al.* (1987), Erwin *et al.* (1990), Picton and Costello (1999), and unpublished data within the EcoServe database.

Region 1. Muddy sediment characterised by a variety of infaunal polychaete species and the bivalves *Abra* spp. and *Nucula* spp. in grab samples (Fox *et al.* 1996, Hensley 1996). This region is the centre of the commercially important Dublin Bay prawn *Nephrops norvegicus* fishing grounds.

Region 2. The Lambay Deep seabed is muddy sand characterised by large numbers of the brittlestar *Amphiura filiformis*, with the brittlestar *Ophiura albida* and burrowing sea urchins *Echinocardium* spp. (Costello and Emblow, unpublished data).

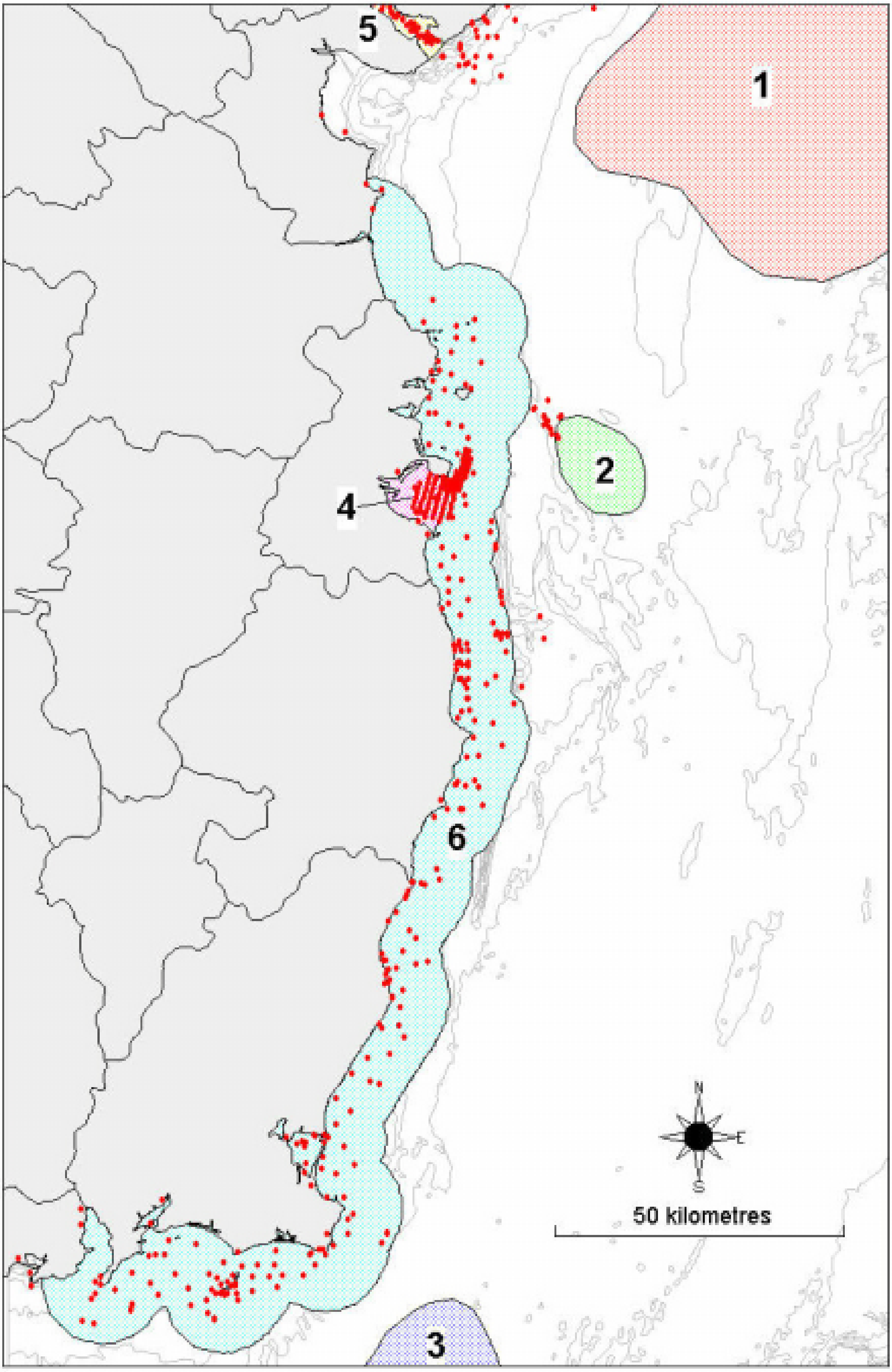
Region 3. The Celtic Deep has a muddy polychaete dominated infauna with similarities to that of Region 1 (Mackie *et al.* 1995).

Region 4. The Dublin Bay fauna is characterised by amphipod (*Ampelisca* spp., *Pontocrates arenarius*), bivalve (*Nucula* spp., *Fabulina fabula*), and polychaete (*Sigalion mathildae, Lanice conchilgea, Magelona* sp., *Prionospio* sp., and *Scoloplos* sp.) species typical of shallow sand seabed's (Walker and Rees 1980, Benthos Research Group 1992).

Region 5. Carlingford Lough contains a wide range of seabed substrata. A diving survey recorded mud characterised by the sea pen *Virgularia mirabilis*; sand by *Ophiothrix fragilis, Arenicola marina,* and burrowing sea urchins (*Echinocardium cordatum, Spatangus purpureus*); shallow cobbles by the tunicate *Ascidiella aspersa* and several species of red algae; shallow rock by kelp (*Laminaria hyperborea, L. saccharina*) and other algae (*Cladostephus spongiosus, Sphacelaria plumosa*) (Erwin *et al.* 1990).

Region 6. The most widespread habitat in the western Irish Sea is current swept coarse sediments. These consist of compact sand, with gravel, shell and/or cobbles in varying proportions. The fauna is characterised by erect hydroids (typically *Hydrallmania falcata, Sertularia argentea, Nemertesia* spp.) that attach to cobbles or shell (Keegan *et al*. 1987, EcoServe unpubl. data). The bryozoan *Flustra foliacea* is abundant on bedrock exposed to strong currents and sand scour. Other habitats in this region include

(a) banks of cobbles, gravel or horse mussel (*Modiolus modiolus*) shells on which the brittlestar *Ophiothrix fragilis* can be very abundant (e.g. Codling Bank, Costello and Emblow, unpublished data).
(b) duned gravel with few species except for the sea cucumber *Neopendactyla mixta* (Costello and Emblow, unpublished data)
(c) coarse sands characterised by the polychaetes *Nephtys cirrosa, Ophelia borealis* and *Lanice conchilega*, and bivalve *Spisula elliptica* (Keegan *et al*. 1987),
(d) bedrock and boulders with a species rich fauna dominated by sponges, hydroids, and anthozoans in deeper water, and these taxa with algae in shallower water (Costello and Emblow, unpublished data).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Assessment of Impact of Offshore Wind Energy Structures on the Marine Environment

Prepared for

The Marine Institute

Volume II

Supplementary Report: Review of Knowledge on Artificial Reefs

Prepared by

6.9 School of Ocean and Earth Sciences, University of Southampton

Certified Final Report

Date: March 2000
JBS: 07.01.07
Doc No: 303-X001

Declaration

Executive summary

Artificial reefs are used world wide as a tool in fisheries and coastal zone management.

World leaders in artificial reef technology are Japan who include reefs in their effective national fisheries creation plan which has modified some 10% of the Japanese coastal environment. The Japanese generally use engineer designed structures in steel and concrete (although wood and Glass Reinforced Plastic are also used) placed for community management by the coastal fishers. Funding is a mix of national and local government, and local fishing communities. Government funding is reliant on the use of approved standard designs, effectively ensuring control of reef construction and an effective subsidy for steel and concrete industries.

In the USA the national plan looks to State initiatives to develop reef programmes. The most active reef deploying State is Florida. Much use is made of 'materials of opportunity' leading to criticism that artificial reefs are just a legitimised form of dumping. This is not totally fair as all materials have to meet EPA requirements before deposit. Emphasis is on reefs for recreational use, especially for angling but other uses such as environmental mitigation are seen.

Europe has been deploying reefs for 30 years or so with a variety of objectives. Activity is focused in southern Europe with Italy, France, Spain and Portugal all deploying reefs along sections of their coast. Deployment is on a much smaller scale than seen in Japan. The dominant material is concrete. Artificial reefs have been placed in European waters to achieve, at least at a pilot scale:

(1) Protection of sensitive habitat.
Artificial reefs have proven to be effective in preventing trawling in waters shallower than 50 m in the Mediterranean and 100 m in the Cantabric Seas, protecting valuable and sensitive seagrass and benthic algae habitats essential to the well being of many animal species. The total area protected is very small in percentage terms but Spain in particular has developed this technology and is expanding its reef deployment programme.

(2) Promotion of fisheries yield.
Local fishery yield has been increased by reef deployment. The scale is small but effective. An additional benefit of excluding trawlers from shallow water has been to encourage local artisanal fishermen and provide income for local communities. The pragmatic outcome is welcomed but the underlying processes are not well understood and fishery management initiatives are often ignored by the fishermen reefs are meant to help.

(3) Promotion of reef related aquaculture.
Development of bivalve aquaculture in the Adriatic Sea provided the best example of reef related aquaculture. The reef units are used as anchors for mussel cultivation ropes and suspended growth of European and Pacific oysters and so produce additional complexity to the overall reef (Fabi and Fiorentini, 1997). This provides additional niche opportunity for fish and so both wild fishery and aquaculture can flourish. The reef design had developed and is now in commercial application at four Adriatic sites. Mussel harvesting is the main application and yields of 20-55 kg m^{-2} have been recorded. Average income from a reef site is estimated at 258,000 US$, allowing reef deployment costs to be recovered in about five years. Research also supports the concept of lobster ranching, hatchery technology is established and survival to market size together with reproductive activity proven.

(4) Increased understanding of epibiotic community development.
Most artificial reefs have been studied to provide a description of the colonisation process. The development of both sessile and mobile fauna dominates these type of studies. Comparison shows the expected differences between temperate and Mediterranean conditions and oligotrophic and eutrophic waters. Colonisation in temperate and eutrophic waters seems to stabilise after about five years whilst oligotrophic communities may still be developing ten years after immersion.

(5) Increased understanding of animal behaviour and use of artificial structures
Diver observation and tagging together with telemetry have improved the knowledge of how some species exploit reef spaces. There is still a lot of work to be done but the recognition that reef design requires an understanding of what the target species requires is driving the work forward. Development of telemetry systems for artificial reef applications has been led in Europe by the Southampton artificial reef group with the development and application of electromagnetic telemetry to lobster behaviour in the field and laboratory (Collins *et al.*, 1994a,1997a; Jensen and Collins 1997; Smith *et al* 1998,1999). Such research to define the parameters required for target species rather than an assumption of requirements made by a human CAD package operator, or in many cases left to educated chance is an important aspect of European reef design and development in the future.

(6) Nature conservation.
The first reefs deployed in Europe, off Monaco in the 1960’s, were placed to provide habitat for marine life and so promote nature conservation. This work has continued in the development of artificial cave habitats for the over-exploited red coral. Developments of marine parks and marine reserves in other areas of the Mediterranean have used artificial reefs to effectively prohibit trawling as well as adding habitat diversity, which usually increases species diversity. The success of these protected parks has provided increased value to the "anti-trawling" reef initiatives.

Spain currently has 9 marine reserves. In most of these marine reserves some kind of artificial reef has been placed.

(7) Assess the environmental suitability of waste materials in artificial reef construction.
Both Italian and UK projects have tested cement stabilised pulverised fly ash (PFA) extensively and shown it to be non-toxic and provide a material for construction and biotic colonisation. This success and development of test protocols has encouraged interest in the assessment of tyres and stabilised quarry slurry and harbour muds as reef materials.

(8) Windfarm breakwaters as artificial reefs
The 'artificial reef function' of such a breakwater would be secondary to its primary purpose but the provision of hard habitat in coastal waters opens up opportunities for habitat protection, commercial fishery exploitation, recreational uses for angling and SCUBA diving as well as 'offshore' suspended, cage and bottom aquaculture.

Breakwaters may also be used to divert water currents to promote the successful settlement of commercial species or as advanced coastal defense structures, absorbing wave energy away from the beaches.

Whatever the final choice of secondary function the selection process must involve extensive stakeholder dialogue and any chosen site must be fully assessed before structures are proposed so the secondary benefit can be maximised and all implications of deployment recognised.

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General background and history of artificial reefs

Marine artificial reefs have been defined in 1996 by the European Artificial Reef Research Network (EARRN) as 'submerged structures deliberately placed on the seabed to mimic some characteristics of a natural reef'. Stephan *et al*. (1990) state that 'artificial reefs represent a tool by which man can elicit changes in the ecosystem to achieve benefits'. Many different artificial reefs have, for a long time, been placed in many different environments throughout the world. The use of artificial reefs as fishing sites has a long history, presumably arising from chance observations of fish being attracted to objects placed in the water. An European example comes from Italy; in Sardinia tuna have been caught for hundreds of years in complex floating net traps weighted with stones. At the end of each season the stones were cut loose and fell to the seabed. Fishermen noticed how many fish species were attracted to these accumulating piles of weights and fished these “accidental” reefs outside of the tuna season.

Artisanal fishermen in tropical countries without any scientific or engineering assistance have probably built the majority of inshore artificial reefs and fish attracting devices (FADs). Such reefs increase catches in local fishing grounds using simple, readily available, materials such as rocks, trees, bamboo and scrap tyres.

Artificial reefs are habitat enhancement devices placed in the marine or freshwater environment to provide, in the best examples, a specific habitat preference for target species. By increasing the carrying capacity of the natural environment their purpose is to increase the overall productivity. Artificial reefs have been used for centuries by coastal communities and have become popular fisheries management tools worldwide (De Silva, 1989; FAO, 1990).

Traditionally, artificial reefs have been constructed for fishery enhancement, but they are now built to serve a number of purposes in coastal zone management:

- improvement of fishing catches and quality;
- provision of spawning areas, and protected juvenile and finfish habitats;
- shellfish and finfish ranching to protect and or supplement natural stocks;
- shore protection and control of beach erosion;
- breakwaters;
- preventing trawlers from using certain areas;
- restricting fishermen from shipping lanes;
- reduce fishing pressure on defined stocks;
- mitigation and restoration of degraded habitats;
- amenable SCUBA sites in sheltered areas;
- waste disposal options;
- scientific experimental grounds;
- recycling of nutrients in areas where bivalves (molluscs) are farmed;
- resolve potential conflicts between user groups of the marine resource.
- recreational angling
- recreational surfing

Artificial reefs function as fishery enhancement devices because they resemble natural reefs. In general, they show a similar species composition and community structure to natural reefs in the same area, assuming they are subject to the same environmental conditions (Ambrose &

Swarbrick, 1989; Bohnsack & Sutherland, 1985; Matthews, 1985). Algae and invertebrates usually colonise new reef materials fairly rapidly. The final composition and abundance of the artificial reef community may vary considerably, depending on the composition of the substrata, the season the material was deposited and numerous environmental variables, including water movement, water temperature and water chemistry. The depth at which the reef is situated is also important, especially with regard to algal colonisation. After initial colonisation, populations often fluctuate cyclically or seasonally. Assemblages of biological communities may be affected by competition, predation and physical disturbance (Bohnsack *et al*., 1991).

Fish also recruit rapidly to an artificial reef, sometimes within hours of installation (Bohnsack & Sutherland, 1985). They often reach a climax population size within a few months of deployment, creating an enhanced fishing zone up to several hundred metres from the reef. Larger catches are however, generally limited to within 60 m (Mottet, 1981). An equilibrium community structure is usually achieved within 1 - 5 years, although there are often seasonal variations in the number of species and individuals.

A wide variety of environmental cues are thought to play an important role in attracting fish to such devices, including: current patterns; shadows; species interactions; sound; touch; pressure; and visual cues of size, shape, colour and light (Bohnsack & Sutherland, 1985). Different species exhibit different behavioural preferences throughout their life cycle. In particular, several fish species have been shown to stay near artificial structures for protection when small and vulnerable to predation (Anderson *et al*., 1989). An artificial reef can be important for the fish stocks of a much larger area than the reef itself, because it gives protection to the fish during their most vulnerable stages. Some Japanese reefs, for example, are built to improve spawning, recruitment and survival of animals during the early stages of their life histories (Mottet, 1981).

In general, the abundance and diversity of species at an artificial reef depends on suitable living conditions, a supply of recruits and a higher recruitment and immigration than mortality and emigration. Suitable living conditions may include: access to food resources, shelter from predators, and normal environmental conditions that are within the biological tolerances of the species (Bohnsack *et al*., 1991).

Artificial reefs have been constructed from many types of material, both natural and man-made. They range, in size and material, from simple wooden constructions, to engineered steel and concrete structures, as well as "materials of opportunity" such as car tyres, old cars and abandoned offshore installations (Kjeilen *et al*., 1994). An artificial reef area can be composed of single reef units, groups of units, or a larger reef complex comprising several groups of reef units. The majority of artificial reefs have been deployed in inshore, shallow waters (Kjeilen *et al*., 1994).

Japan has been one of the leading countries that have used artificial reefs as fisheries management tools, dedicating at least 10 % of its coastline to marine enhancement devices (not all these are artificial reefs). Japan has invested considerable effort into the optimisation of reef layouts and construction. The USA has also appreciated the opportunities of recreational fishery enhancement derived from artificial reefs and has initiated a national artificial reef programme, each coastal state develops reefs using both engineered reefs and materials of opportunity.

Despite the large investment in artificial reefs in certain countries, the ecological basis behind artificial reef function and biology is, presently poorly understood and is, increasingly, the focus for future research. The variety of materials used and the broad range of conditions in which reefs are deployed limits the conclusions that can be made. Nevertheless, at artificial reefs, high fish densities, biomass and catch rates, in addition to rapid colonisation, are well documented (Bohnsack *et al*., 1991; Bohnsack & Sutherland, 1985), and are often found to be higher on artificial reefs than on natural reefs or randomly selected bottom controls (Ambrose & Swarbrick, 1989; Bohnsack *et al*., 1991; Bohnsack & Sutherland, 1985; De Martini *et al*., 1989; Fast & Pagan, 1974; Hueckel *et al*., 1989; Laufle & Pauley, 1985). Also, artificial reefs generally serve to attract more commercially valuable species than those associated with soft sediments (Seaman *et al.*, 1989). This has been attributed to the greater complexity offered by artificial reefs.

Overall, artificial reefs are thought to aggregate existing scattered individuals and allow secondary biomass production by (Bohnsack & Sutherland, 1985; FAO, 1990):

- increasing survival and growth of larvae and juveniles by providing a settlement substratum, shelter from predation and additional food resources;
- creating new food webs through the provision of new spaces, habitats and colonisation patterns;
- protecting the sea-bed and nursery grounds;
- recycling energy by retaining a localised ecosystem.

There is concern that artificial reefs can cause over-fishing. In some instances this has occurred (Polovina, 1989). Evidence from several researchers however, indicates that reef deployment increases the fish populations of particular species without interfering with the natural fisheries of adjacent habitats (Alevizon & Gorham, 1989; Bohnsack & Sutherland, 1985). Over-exploitation of reef-associated fish stocks is generally not expected as a consequence of artificial reef deployment (Bohnsack & Sutherland, 1985), because artificial reefs can generally be expected to provide both fish aggregating and biomass producing qualities (Bohnsack *et al*., 1991). It should be noted that the concerns over fishing pressure are only valid if the management plan that should accompany a reef allows fishing.

Research scientists are active throughout the world, working on a wide range of reef related questions in what is a fairly new branch of marine science. The majority of the work has focused on establishing what happens when a reef is deployed, considering speed and "naturalness" of colonisation by animals and plants and the implications of this for habitat protection or fisheries exploitation. Scientists frequently work on artificial structures placed for one purpose in order to investigate other uses. In an European context we see fisheries investigations around reefs placed to protect habitat and behavioural studies on reefs placed as material test sites. This does not negate the value of work done but it is important to realise that a lot of results are derived from "structures of opportunity" rather than reefs purpose-built for the scientific project being undertaken.

International communication between scientists is maintained by a four yearly international conference (most recent meeting was 7-11 October 1999 in Sanremo Italy) and, since 1995 in Europe, by the European Artificial Reef Research Network (EARRN). Engineering interests have become involved in the design and deployment of artificial reefs (as seen in Spain, Hong Kong and Japan) where civil engineering companies see a commercial market developing for such structures. Such companies can be very influential in design and construction, seemingly often designing reef structures without formal research into the requirement of target species, relying on trial and error and human aesthetics for many design developments.

In summary, artificial reefs are used to:

- enhance fisheries by creating fishing opportunities,
- reduce user conflicts,
- save time and fuel,
- reduce fishing effort,
- make locating fish more predictable,
- increase public access and safety by deployment near ports, and
- increase fish abundance at deployment sites by attracting dispersed fish and producing a new fish biomass.

Commercial invertebrates have, to a large extent, not featured in this evaluation but there is increasing work being undertaken in northern Europe and eastern USA on reefs for lobsters. It has been suggested that the most likely applications for artificial reefs in commercial fishing are to create or expand existing nursery or spawning grounds for some species (Sheehy, 1985) or in the case of lobsters provide new habitat or modify existing natural reefs (Jensen & Collins, 1997). Stocking in specially prepared and enhanced areas can also improve the initial survival and growth of juveniles (Sheehy, 1985).

Review of artificial reefs in Japan, USA and Europe

Japan

The Japanese are the world leaders (by a considerable margin) in artificial reef technology for commercial fishing enhancement and have been creating artificial reefs since (at least) the 18th century. Currently Japan is in the third phase of artificial reef development, that of creating entire fishing grounds where there had been none before, a significantly more sophisticated philosophy than the patch work development of structures seen elsewhere in the world. This programme commenced in 1974 with the goal of diverting Japanese fishing effort from distant water fishing (where it was meeting increasing resistance) to mariculture and resource management in Japanese waters. Government investment has been substantial; for example in 1988 US $150 million was allocated to subsidise the construction of 2.2 x 106 m^3 of fishing reefs, 10% of the coastline has been influenced by artificial reef deployment or other modifications designed to enhance yield of sea food.

Deployment of artificial reefs in Japan is well regulated. The engineering and design aspects of Japanese artificial reefs are well refined, and make use of many different lattice type shapes. These are apparently effective in attracting mid-water and demersal species and large, high profile lattice structures have been developed. Designs such as the Kobe steel reef, N-F reef, NSC type steel reef and NSM steel reef, in the region of 11 m^3 weighing 33 tonnes, resemble small oil production platforms. Quality standards regarding building materials, design, location and construction exist which must be complied with if structures are to qualify for government certification and subsidy. However, it appears that the biological appraisal of artificial reef performance is not so well advanced. Some workers have concluded that there are insufficient biological and economic data for judging the cost effectiveness of many of the reef deployment operations. The Japanese judgement is more pragmatic; their artificial reefs work (in that they provide effective fishing locations), and are worthy of development, because they (a) enhance the harvesting of food from the sea (a major component of the Japanese diet), and (b) contribute significantly to the well-being of the coastal fishing communities that effectively own and manage the artificial reefs (Simard, 1997).

Japanese reef development is linked to the use of concrete and steel (and some GRP) as the main construction material. In general waste materials are not used, although plans are well advanced to use pulverised fuel ash for submarine banks, a significant new material for a fairly ambitious project. By indicating a preference for steel and concrete the Japanese government are effectively directing public monies that support reef developments into domestic engineering industries, a useful spin-off from reef development.

Coastal communities in Japan frequently manage artificial reefs. The social structure of interaction within and between fishing communities is well defined and each has historic rights to harvest specific areas of the seabed. By developing reefs within this existing effective and transparent system the fisheries managers in Japan have a proven management structure in place as soon as the reef is deployed.

USA

American experience of reef construction dates back over 100 years and in that time a variety of (mostly waste) materials have been used including: concrete, rock, construction rubble, scrap tyres, cars, railway carriages and ships. Recent high profile examples have been battle tanks and fighter aircraft deposited in the Gulf of Mexico. The USA is "home" to the original "rigs to reefs" programme. The USA has a national artificial reef plan but no government funding commitment. Funding has come from the Federal Aid in Sport Fish Restoration Program, which may provide up to 75% of reef construction costs, with individual States providing the rest. In 1987 more than US $140 million was provided by the Federal Aid Program. The most active state is that of Florida which has placed over 100 structures along its Atlantic and Gulf coastlines.

The artificial reef programmes of many maritime States are run to benefit recreational sports fishing, SCUBA diving, commercial fishing, assist with waste disposal and provide environmental mitigation. Artificial reefs are generally perceived as a "good" thing in the USA and whilst scientific evidence is part of the appraisal process for environmental mitigation, the sports fishing reefs are judged to a large extent by "customer satisfaction" criteria.

Artificial reefs are most frequently deployed to improve sports fishing which is recognised as an important industry with significant socio-economic benefits to coastal communities. It is important to recognise that recreation in the USA is of much greater importance and is taken much more seriously than in Europe. In the USA artificial reefs have been encouraged on a "low or no cost basis". With the help of national legislation coastal states have defined sites where reefs may be deployed and in many cases a small group of state employees or enthusiastic volunteers have been involved with the acquisition of materials to create reefs. More often than not these are "waste" materials or "materials of opportunity" and the cost of deployment is absorbed by the organisation "donating" the materials. The process follows fairly simple economics; does placing a suitable material in the sea, after cleaning, cost less or a similar amount to onshore disposal or recycling, given that politics and PR are in support of the idea? If so then reefs will be deployed. Reefs have been constructed from a wide range of materials such as old vessels, battle tanks, computer hard disks, old toilets, building rubble tyres and so on. This type of deployment gives rise to the complaint that reef creation is just a legalised method of dumping waste at sea, something that reef legislation (and most credible reef researchers) seeks to prevent. The general aim has been to create new sites for sports fishing that are convenient in that they are close to ports, well marked and provide good catches of fish on rod and line. "General purpose" artificial reefs are created because knowledge of the required target species habitat is limited as is choice of materials. Criterion for success are based on rod and line catch, number of people fishing or using the reef and "charter boat satisfaction" (which translates into tourist dollars) rather than a hard "cost benefit analysis" based on commercial fisheries. The use of rod and line appears to pose no serious threat to the fish populations attracted to these structures.

Little concern is expressed by other than researchers as to how the systems work and why. Such generalised reefs appear to increase the overall local biodiversity, another factor that is seen as "good".

The use of steel jackets from oil and gas production platforms in the Gulf of Mexico is an extension of this philosophy. This area holds the majority of the world's production platforms, some 4000 compared to about 400 in the North Sea. Platforms tend to be much smaller than those in the North Sea and they have been in place for much longer. The use of obsolete jackets to create artificial reefs is based on a "mutual benefit" philosophy unique to the USA and it's historic way of creating artificial reefs from "waste" materials. It is worthy of note that the success of the Gulf of Mexico programme has not been translated to the southern west coast of the USA. In the latter, the concept of rigs to reefs is meeting opposition from environmental NGOs and local lobby groups who wish to see oil producers meet the full cost for rig removal and clean-up.

Europe

Introduction

At present most European reefs are still associated with scientific research of some type. In Europe artificial reefs were pioneered in Monaco for nature conservation in the late 1960s (Allemand *et al*., 1999). Artificial reef research programmes have now been initiated in eight countries of the European Union (EU) (Italy, Spain, Portugal, the UK, the Netherlands, Finland, Greece and France (Jensen *et al*., 1999). In addition, countries such as Ireland and Denmark (Stottrup, pers. comm.) have a strong interest in artificial reefs, although no structures have, as yet, been placed (as far as is known). Norway has a strong interest in the 'rigs to reefs' concept (Aabel *et al*., 1997,1997a) and some experimental concrete units, based on Japanese designs have been deployed (Per Jahren pers comm.). Outside the EU, Poland has deployed experimental structures in the Baltic, Turkey has a small experimental programme based in Ege University (Jensen *et al*., 1999). Romania (Dorogan pers. comm.) and Ukraine have placed some reefs for experiments into biofiltration in the Black Sea. Israel has been active in the field for some time, deploying tyre structures in the Mediterranean (Jensen *et al*., 1999) and having an interest in structures placed in the Red Sea. Russia is involved with reef interests in the Baltic (Antsulevich *et al.*, 1999) and has built reefs in the Caspian sea, the SADCO-SHELF programme.

Reef building has, until relatively recently, been carried out nationally, with little cross-border co-operation. This is changing; in 1991 Italian artificial reef scientists formed an Italian reef group to encourage liaison between research groups. An association of Mediterranean artificial reef scientists now exists. Artificial reef research in Europe has reached a stage where scientific priorities for the future need to be developed in the light of previous research and experience. This is the aim, and the reason for the creation, of the European Artificial Reef Research Network (EARRN) funded by the European Commission "AIR" programme.

Materials used in reef construction

Concrete is the most commonly used material for reef building in the EU. Concrete is considered an acceptable material, mainly because of its general acceptance within the construction industry. It provides a well understood, cost effective and "plastic" material that can produce reef units of many shapes and sizes, restrictions come only in the practical considerations of moulding the wet concrete.

Quarry rock has been used in circumstances where even concrete was considered to be unacceptable (Holland) as a reef building material.

There is a sensitivity to the re-use of materials that may be described as waste, as there is concern that artificial reef construction will be used as a means to illegally dump rubbish/waste in European seas, leading to contamination by pollutants leaching into the sea. In addition there is a strong lobby which philosophically opposes the placing of any waste material in the sea, regardless of its character. The fact that concrete contains a high level of Pulverised Fuel Ash (PFA) sourced from coal fired power stations, which is a waste material does not appear to register with either group. Concrete is considered to be acceptable because it is a familiar building material and has been accepted by the construction industry as such. Against this background scientific work has progressed the knowledge relating to waste materials used in artificial reef construction, especially in the UK and Italy.

There is a valid concern that placing waste materials in the sea may lead to release of potentially harmful substances into the sea and incorporation into marine food chains. Much of the scientific research into stabilised materials described below has directly addressed this issue. However there is considerable non-governmental organisation opposition to placing *any* waste material in the sea. No distinction appears to be made between types of waste material. This argument is based on a philosophy rather than a scientific appreciation of the nature of the material in question. A consequence of blocking any marine use of recyclable materials would be the accumulation of such materials on land where the environmental affects may be negative rather than positive.

Legislation and legal requirements

There is little or no EU specific legislation relating to artificial reef deployment. The construction of a reef therefore fits within both EU and national legislative requirements. This makes for a complex situation which has been extensively reviewed by Pickering (1997).

European reefs are subject to some form of permitting system throughout the EU. The application for a permit is reviewed by government organisations who are responsible for the country's compliance with international legislation as well as it's own national requirements.

The principal international legislation covering the deposition of waste and other matter in the ocean is the London Convention, 1992 (formerly the London Dumping Convention). Placement of material for the construction of artificial reefs in not covered by the Convention. However aware of the range of materials that have been used for such purposes, the London Convention Scientific Group has recommended that the guidance prepared for the interpretation of the Annexes to the Convention in relation to dumping at sea contains all the considerations that are needed for the assessment of placement of an artificial reef or structure. The recently revised OSPAR (Oslo/Paris) Convention, (Convention for the Protection of the Marine Environment of the North East Atlantic) covering the north east Atlantic area, includes placement of matter such as ashes within its purview and is establishing a set of technical guidelines for the practice. Similar organisations, but with different guidelines exist for the Baltic, (Convention on the Protection of the Marine Environment of the Baltic Sea Area (Helsinki Convention)) and the Mediterranean (Convention for the Protection of the Mediterranean Sea against Pollution 1977 (Barcelona convention)) In each country that is a signatory to the OSPAR convention a government department (often the fisheries department) will have responsibility for licensing artificial reefs and ensuring adherence to the guidelines laid down by international treaties and in the case of an artificial reef application will apply the guidelines of the OSPAR convention as well as consulting widely. In general the government departments with responsibility for fisheries and/or the environment will be responsible for processing an application to place an artificial reef and will consult as widely as considered necessary. Below this level local government may become involved, to what extent relies on the normal procedures within the country in question.

There is no doubt that the legislation is a procedural "minefield" for applicants and may reef developers in southern Europe complain about the excessive administration involved with reef deployment. Of all the European countries Spain probably has the most explicit artificial reef legislative procedures and these are far from easy to follow (see Revenga *et al.*, 1997).

One component of European legislation that has been utilised by Spain and Italy for funding artificial reef construction has been the series of Multiannual Guidance Programmes which have provided funds for the de-commissioning of the large EU fishing fleet. The programmes provide 50% funding for initiatives to reduce fishing effort. Italian and Spanish artificial reef programmes have been seen by their governments as a means to prevent trawlers fishing in waters shallower than 50 m (100 m in north Spain) and damaging sensitive seagrass habitat. So called "anti-trawling" reefs have been promoted by government in attempts to reduce illegal trawling, protect a sensitive habitat and encourage artisanal static gear fishermen from local coastal communities. The latter use techniques that are better targeted at commercial species than trawls

Deployment configurations

There is not single plan for reef configurations in Europe. Most artificial reefs are deployed according to engineering and/or scientific design. In the worst cases reefs have been deployed by political decision and scientific monitoring involved only later in the decision-making process. Few, if any, of these politically motivated reefs have fulfilled expectations as their locations were poorly chosen (Moreno pers.comm; Haroun pers. comm.).

The majority of European reefs have been placed to deter trawling in the Mediterranean Sea. In general reef units have been dispersed in areas of seagrass beds to present a physical barrier to trawling. Reef units have been made heavy enough to prevent them from being towed from position and/or have spikes to maximise the net catching and ripping potential. One reef, off Loano, north west Italy, several km^2 in area, is monitored by marine police, making any interference to the reef units subject to an immediate armed police response.

In more extensive reef fields the reef units have to provide all the deterrent effect. The reward from fishing in seagrass beds is high so trawlers are not easily discouraged. Boats may "pair-up" to tow obstructions from their path so that the trawls can pass without damage. There is an on-going contest of wills between the trawl fishermen and the reef planners. Reef field design has peaked under these conditions, reef units and their distribution are designed to make the units immovable by boats with a given engine power and units are placed to provide maximum obstruction per unit. (Sánchez-Jérez and Ramos-Esplá,, 1995; Sánchez-Jérez and Ramos-Esplá, in press).

Artificial reefs in Europe usually have some scientific research taking place. In most cases this research has had some influence on the reef layout, at least in part. Purely scientific reefs, such as seen in Poole Bay, UK are often laid out to provide replicate structures to aid scientific statistical analysis. Often the layout is part of the experiment with identical reef units being placed in different environmental conditions. These may be depth or as in the case of the Gulf of Castellammare in Sicily in eutrophic, oligotrophic and mixed water conditions (Arculeo *et al.*, 1990; Badalamenti *et al.*, 1985; Riggio *et al.*, 1995a; Riggio *et al.*, 1995b).

Location is normally the result of a consultation process with other users and relates to the use of the reef or a request from a coastal community (seen in the Adriatic Sea). The former was taken to a technological level by Heaps *et al.* (1997) by entering all information into a GIS and comparing the result with a more conventional selection process. The results coincided.

Management programmes

With a few exceptions there are no specific artificial reef management programmes in Europe, the reefs are usually part of a desire to manage or influence processes in the marine environment and usually this includes increasing fishery yield. Whilst the reefs are not, in themselves, managed they are monitored by marine scientists, usually biologists, and so sizable amounts of data exist on benthic community development on reef surfaces and presence/absence of fish species.

Where EU money has been used there is now a mandatory 5 year monitoring programme put into action. This provides a means of describing the biotic colonisation of reef surfaces, development of fish populations, impacts on the physical environment and assessment of fishing yield from reefs.

The majority of European artificial reefs are Mediterranean and the concept of fishery yield enhancement is very important to the use of reefs. There is no solid, irrefutable scientific evidence to support the claim that reefs increase the overall biomass of fish in areas in which they are placed, but it seems intuitive that the possibility of enhancing numbers of a species that use reefs for spawning and/or nursery grounds must exist and should be recognised. This concept can be extended to species that utilise seagrass habitats where they are protected from physical damage by trawls. The argument for the increase in pelagic species is not so obvious, if such an advantage exists it will be related to some aspect of feeding opportunity, shelter from currents or predators or similar advantage during a phase in the life history.

What is seen is the aggregation of some species around artificial reefs, a proportion of which are commercially important. Reefs become a focus for effort and so concern is expressed that reefs cause overfishing. The reality is that this is hard to prove either way, arguments against reefs suggest that all fish in a given area will congregate and be caught, pro-reef arguments generally run along the lines that fish population assessments are not good enough to quantify the presence/absence of all fish, evidence from catches suggests that fish are present both around and at distances (several kms) away and that the scale of the reefs is too small to seriously influence fishery dynamics. Data to clarify this argument does not exist.

What does seem to be important is the introduction of a fishery effort management plan with the reefs. This should seek to control effort whilst populations establish and then control exploitation of resident and "visiting" species. European reefs are just not big enough to be self sustaining and fishing exploitation should (but rarely is) be linked to the ability of the structures to attract post larval fish and other commercial species and support them until MLS is reached.

What fishery plans exist are often ignored by the fishermen, unless the presence of the reef prevents fishing, and there seems to be a variable response to this by authorities.

Country by country synopsis of artificial reef development

United Kingdom

Two deliberately placed marine artificial reefs now exist in the UK, one in Poole Bay, on the central southern English coast deployed in June 1989, and off the south eastern Scottish coast near Torness, deployed in 1984. In 2000 a reef 'project 2000' will be deployed in Loch Linne off the west Scottish coast.

The Poole Bay reef was deployed as a material test experiment. The reef consists of blocks made from stabilised Pulverised Fuel Ash (PFA), a waste material from coal fired power stations bound with cement and aggregate. The reef has been continuously monitored to investigate the biological colonisation and the fate of the heavy metals bound within the coal. Results suggest that the heavy metals are secure within the blocks, that colonisation is rapid and that reefs do provide a good habitat for lobsters and other commercial shellfish (Jensen *et al.*, 1999a,b) .

The Torness reef was constructed from quarried rock derived from the construction of a nuclear power station. The reef is investigated infrequently to determine biological colonisation, fin-fishery potential and shellfish fishery potential. To date the reef has not been found to support significant amounts of any commercial species although biological colonisation has been good.

Other workers in the UK are interested in the utilisation of artificial structures for lobster stock enhancement and the decommissioning of North Sea oil rigs in such a manner as to provide artificial reefs, some for fishery enhancement.

Italy

Italy has seen considerable artificial reef activity. The Italians were among the first serious European users of artificial reefs and are well organised on a national basis. Many programmes have been assisted by 50 % EU funding and both local government and fishermen's organisations are involved in encouraging the programmes. Several programmes are predominant.

Loano artificial reef

An "anti-trawling" reef system was set up in the Ligurian Sea during 1986 (Relini, 1999a) to protect the natural environment and in particular *Posidonia* beds from bottom fishing gear towed by trawlers. Trawling is prohibited in waters shallower than 50 m in the western Mediterranean (Italy, France and Spain) and 100 m off the northern Spanish coast. Researchers based at Genova University have studied the effectiveness of the protection from trawling as well as investigating the settlement of benthos and colonisation by fish.

Results show that the reef units provide effective protection against trawlers.

Seasonal and successional changes of the reef communities have been noted. Cement panels immersed at different depths revealed 117 species of sessile animals and 76 algal species had colonised. Sixty-six species of fish and cephalopods were listed, some of these utilising the reef for reproduction. Endangered species such as groupers (*Mycteroperca rubra; Epinephelus marginatus*) appeared in the vicinity of the artificial reef. They are very rare in the Ligurian sea.

CENMARE - Coal ash for artificial reefs

There is an interest in the constructive use of power station waste (Pulverised Fuel Ash, PFA) for artificial reef construction. As in the UK great emphasis has been placed on the environmental suitability of such material and a large tank trial was undertaken by workers from Genova in 1990 and 1991. Epifaunal settlement on the ash blocks proved greater in quantity and better in quality than that on the control (concrete blocks) (Relini, 1999b).

Biomass measurements confirmed the qualitative and quantitative differences seen in the biological indices between the epifaunal communities. Given the biological colonisation and the physical and chemical stability PFA seems to be a suitable material for artificial reef construction.

Fregene artificial reef

Deployed in the central Tyrrhenian Sea, 9 km from the mouth of the river Tiber in 1981, this reef is subject to severe siltation. It has been studied primarily to gain an insight into the way fish and epifaunal communities' change over time and with environmental conditions (Ardizzone *et al*., 1999). Over the 11 years of study the reef fauna has changed from a pioneer community to a mussel dominated community, which was not harvested. The mussel community declined over time as siltation and lack of colonisation prevented further mussel settlement. Mussel disappearance was linked to the reduction in numbers of fish species and the reef surfaces developed an infaunal population. The development of the sediment community is considered to be a key point in the community development as once established mussels could not resettle onto a surface they had once dominated.

Gulf of Castellammare (North west Sicily)

The project run by the government funded CNR laboratory has evaluated benthic and nekton colonisation, the fishing yields and the trophic relationship between the resident fish and the benthos in the reef area (Riggio *et al*., 1999).

Benthic settlement was characterised by low percentage cover of algae and a large amount of filter feeders. An increase in number of species and species diversity was observed in the nekton assemblage in the reef area in comparison with the control area. Fishing yields were slightly higher in the reef area than in the control area. Resident fish species were observed in the reef area. Stomach content analysis revealed that Sparid fish appeared to prefer feeding around the reefs rather than on natural substrata. Oyster and mussels culture has been successful.

Adriatic Sea

At present at least 11 artificial reefs exist along the Italian Adriatic coast. Seven of these (Porto Garibaldi 1, Rimini, Cattelica, Senigallia, Portonovo 1 and 2, Porto Recanati) were constructed with the scientific support of IRPeM-CNR of Ancona (Bombace *et al*., 1999).

The reef at Porto Recanati was deployed on behalf of IRPeM in 1974 and it was the first Italian reef to be scientifically planned. It is placed in about 13 - 15 m of water and is made of concrete cubes (2x2x2 m) assembled in pyramids each formed by 14 cubes. The cubes provide holes of different shape and size to offer shelter to various species of fish, crustaceans and molluscs. The surface of the cubes is rough enough to facilitate the settlement of bivalve larvae. The pyramids were deployed about 50 m from each other and two old vessels were sunk amongst them. The aims of the scheme were: anti-trawling protection, re-population of biota and development of new sessile biomass, especially mussels and oysters, through the introduction of suitable surfaces. Data obtained showed that initial costs were recovered three times over in about four years through small scale fisheries and collection of the mussels settled on the artificial substrata.

In 1983 IRPeM deployed the experimental artificial reef of Portonovo (Portonovo 1). It is placed in about 11 m of water and made of 4 pyramids; each one of 5 concrete cubes of the same type of those used at Porto Recanati. The reef was used by CNR Ancona for experiments on suspended and immersed shellfish culture (mussel and oysters culture).

The artificial reefs at Porto Garibaldi (1 and 2), Rimini, Cattolica, Senigallia, Portonovo (2) were constructed in the years 1987-89. Five of them (Porto Garibaldi 1 and 2, Rimini, Cattolica and Portonovo 2 were deployed on behalf of local fishermen's associations and represent large scale commercial systems. The aims of reef deployment were prevention of illegal trawling, re-population and mariculture. At these sites, fishing surveys with a standard trammel net were started one year before reef deployment and continued for a few years after. The aim was to compare the effectiveness of the reefs in the different areas in terms of fishing yield and their impact on the fish assemblage of the original habitat. The scientific results obtained from the overall research can be summarised as follows:

- The effects of artificial reefs are more evident at sites far from natural hard substrata.
- Species richness, species diversity as well as fish abundance increased after reef deployment. This increase was particularly appreciable for reef-dwelling nekto-benthic species (e.g. sparids and scienids). The increase in average catch weights recorded for these species three years after deployment of the artificial reefs were 10 - 42 times the initial values. These increments seem to be directly correlated to the reef dimensions in terms of volume of immersed materials and inversely correlated to the distance between the oases.
- Higher catch rates are reported from the artificial reefs in comparison with unprotected areas (Senigallia zone).
- The fish assemblage at the artificial reefs is affected by seasonal fluctuations as well as in the all coastal area. The lowest values are generally recorded in winter, when most of the species migrate to deeper, warmer waters.
- Eventual collapses of fishery stocks living on reefs seem to be mitigated inside the artificial reefs complexes in comparison with unprotected areas.
- In eutrophic waters the new biomass of bivalve molluscs (e.g. mussels and oysters) settled on the artificial structures finds suitable conditions for developing and creates mariculture opportunities.

Gulf of Trieste

The Miranare Reserva Marinara reef in the Gulf of Trieste was placed (in 1978) on a muddy bottom in 18 m of water. Biologists from the University of Trieste have monitored benthic colonisation and fish populations. Whilst sedimentation has limited benthic colonisation (characterised by low % cover of algae) fish are plentiful. A range of species has utilised the reef for reproductive purposes. A seasonal and successional pattern of colonisation has been recorded.

From 1988 concrete pyramids have been deployed off the site of the Marine Biology laboratory at the University of Trieste. The site has been studied to provide data on settlement and colonisation of periphyton and other ecological parameters (Falace and Bressan, 1999). In addition the effectiveness of such structures in preventing trawling activity has been researched.

A reef was deployed in 1994/4 at Dosso, Santa Croce (Gulf of Trieste) Cement structures have been placed to ensure fish re-population and to deter ecologically unsound fishing techniques such as trawling.

France

French activity started in the 1970s with both car bodies and concrete cubes being used in early constructions. Much work focused on the benefits that reefs could make to mariculture, an important element in French coastal economics.

French research workers placed artificial reefs off the French Mediterranean coast (Bouches-du-Rhone, Alpes-Maritime, Languedoc-Roussillon) in the early 1980s. The Bouches-du-Rhone reefs were integrated into local government plans to promote marine life. In all some 3600 m^3 of artificial reefs were deployed, Beauduc (>600 m^3), Cote bleue (2500 m^3) (Charbonnel *et al.*, 1999) and La Ciotat (460 m^3). Natural rock and concrete armed pyramids were used in construction, with an emphasis on anti-trawling reefs (as requested by inshore fishermen).

The Alpes-Maritime reef focused on biological validity of reefs and their socio-economic importance in coastal waters. The use of reefs for habitat amelioration was a particular feature of this programme. Results from these programmes concluded that artificial reefs provided good fish habitat, the artificial reefs sometimes holding more fish than comparable natural reefs.

The results from the third of these reef programmes, that of Languedoc-Roussillon had a significant impact on the direction of artificial reef research in France. This programme, initiated by IFREMER, placed substantial reef, 6000 m^3 of material on a soft seabed in the Golfe du Lion. Commercial net fisheries (mainly for flatfish) were assessed for 16 months before and 16 months after placement of the reef material. The conclusion was reached that although variety of species caught increased in only the second year after deployment, no overall increase in commercial catch could be seen (conflicting with the Italian experience at Senigallia). This result, apparently from a relatively short term study of a poorly placed reef and of species most of which do not require hard substrata, reduced the willingness of the French government research organisation IFREMER to fund research. The protocol of this study, together with the siting of the reef has since been critically reviewed by other workers e.g. Barnabé *et al*. (1999). However, other French organisations maintain significant scientific interest in the field, with scientists continuing to work on existing reefs like those at Port Cros, others collaborating with European based groups such in Monaco and Italy as well as working in the Middle East.

Work has recently started on new reefs in the Golfe du Lion, interest being focused on fish behaviour and the possibilities of shellfish culture on reefs. The work is in progress at present and results are not available. Recent contacts with IFREMER (Lacroix pers comm.) reveal that an artificial reef working group has been formed and may well formulate a strategy for future involvement in artificial reef research.

Portugal

Two programmes are active in Portugal, one off of Madeira, the other on the southern mainland. The reefs off Madeira are in a developmental stage. Since 1983 car bodies, tyres and wooden boats have been used to create artificial reefs in two sites. The aim of the project is to enhance the fisheries potential of the areas and surveys are currently being carried out to establish oceanographic data. A new reef programme is being developed at this time

On the mainland a single programme has evaluated two reefs off the Ria Formosa, an important estuarine system on the Algarve coast (Costa Monteiro and Neves dos Santos, 1999). The aims of the programme were to evaluate the impact of artificial reefs at both ecological and fishing levels and to determine in which way the artificial reefs in the Algarve can be useful as an instrument for fish stock management and to increase coastal resources. The pilot experiment has been successful and phase one of an artificial reef complex costing $3.5 million has been deployed in this area.

Results show that the structures of concrete blocks were physically stable, maintaining reef structure. Biological colonisation of the reefs was rapid during the 1st year after deployment. Seventy-nine fish species were collected on the reef, most of them linked with the fish populations of the neighbouring lagoonal system (depending on seasonal migration to the sea). Chemical studies showed a significant increase of productivity in the reef zones.

Spain

There is extensive reef building activity throughout Spain, over 100 reefs have been placed, coordinated by national government with considerable input from local government (Revenga *et al*., 1997) and 50 % funding from the EU in most cases. At least forty-seven artificial reefs have been constructed, some very extensive in area, mainly with habitat protection (anti-trawling) and/or artisanal fishery enhancement as the main aims. Not all reefs are subject to scientific monitoring but five areas are worthy of note.

Balearic coastal waters

Reefs were deployed to examine the fisheries enhancement potential, the processes of benthic colonisation and the role of artificial reefs in the regeneration of damaged sea bed. The project has assessed the colonisation of the reefs by benthic organisms and the presence and abundance of nektonic species around the reefs since 1991, as well as measuring some oceanographic water parameters.

Results show that benthic flora and fauna naturally cover artificial reef boulders from the first year, a sequence in species and shapes of the organisms is observed. The fish population of the area has increased since the deployment of the reef. The biological 'behaviour' of the reef differs significantly between the various study areas. Differences in artificial reef shape and structure have decisive effects on the biological communities found around reefs of different form (Moreno, 1999).

El Campello (Alicante, Iberian southeastern).

Here artificial reefs have been used to protect meadows of the seagrass *Posidonia oceanica* from damage caused by illegal trawling activity. In the studied area, trawling effects can be seen from 13 to 30 m. Due to the importance of *P. oceanica* meadows to local littoral ecology and fisheries an "anti-trawling" artificial reef has been installed. The reef comprises 358 blocks, in 47 squares, each square being 300 m^2, and 21 dispersed blocks. Work started on the project in 1990, the reef being deployed in 1992. Blocks were arranged in an attempt to protect the maximum area of *Posidonia* meadows against illegal trawling. The protected area is about 5,400,000 m^2, 45 % of which held damaged *Posidonia* meadow.

Since artificial reef installation, in November 1992, no trawling activity has been detected in the area (Ramos Espla *et al*., 1999)

Tabarca Island (SE Iberian peninsula)

This reef was created in 1989 to protect seagrass meadows (25 anti-trawling modules of 8 tonnes) and includes some experimental structures to attract/concentrate pelagic and demersal fish. Oceanographic parameters and planktonic populations were studied in addition to biological colonisation, fish population dynamics and sea grass meadow recovery.

Galicia, Ria de Arousa, (Province of Pontevedra , NW Spain).

Preliminary work led to the implementation of a 2 year artificial reef research programme, starting in July 1993. The need to compensate for the lack of scientific artificial reef research conducted in Galicia has been the main motivation. The influence of depth, degree of exposure and level of organic matter on the ocean floor on artificial reefs will be studied. Artificial reef modules have been installed in two different areas, one at a depth of 20 m and the other at 12 m below sea level.

The monitoring plan involves gathering monthly samples at each location with the purpose of carrying out the following:

- evaluations of the periods in which different types of benthic flora and fauna occupy the artificial reefs,
- numerical estimates of the commercial species based on photographic means, while at the same time
- marking and following the movements of crustaceans as well as surveying the population of bivalve molluscs located in the substratum which is protected by the reefs.

Programa Plurianual de Arrecifes Artificiales. Arrecife artificial de Arguineguin (Gran Canaria, Islas Canarias).

Located in Santa Agueda Bay, to the south of Gran Canaria Island, this reef was placed in the water in 1991, following baseline surveys which started in 1989. The artificial reef is composed of 84 concrete modules of 5 different types. Initial results show that benthic and pelagic communities in the reef area changed dramatically compared those seen in the baseline study. An overall increase in species diversity and biomass has been noted. New species were still colonising the reef two years after deployment. Seasonal and successional patterns of colonisation have started to emerge. The reef biota is now much richer than that on a nearby natural reef, as a consequence of higher sediment abrasion in the latter case. Several species have utilised the reef for reproductive purposes: mating (cephalopods), laying eggs (cephalopods and fish) or releasing larvae (fish). Some fish species have found the reef to be a suitable habitat and become resident. Pelagic fish have been observed feeding around the modules. The reef modules are physically stable (Haroun and Herrera, 1999).

Netherlands

Noordwijk artificial reef

In September 1992 an experimental artificial reef consisting of four, more or less circular, heaps of basalt blocks in a row perpendicular to the prevailing current direction was placed 8.5 km off the Dutch coast at Noordwijk. Each 'sub-unit' is about 1.5 m high and about 10 m in diameter, and consists of about 125 tonnes of basalt, the blocks having a diameter of 20 - 80 cm.

The aim of the project was to investigate the colonising capacity, possible morphological effects on the surrounding sea bottom, and potential modification of the distribution of biomass in the area caused by the reef.

Fish and benthic fauna in the area were assessed before the reef was placed. The species composition and biomass on the reef , as well as fish and benthos up to 1 km from the reef are being monitored 5 times per year. The physical stability of the construction is also watched.

Developments on the reef showed a steadily increasing biomass and diversity which was monitored until the end of 1996. Results have been assessed and although the reef developed a typical North Sea biota (Leewis and Hallie, 1999) a political decision, based on reaction from shrimp fishermen and public reaction, was taken to halt the programme.

Finland

The reef programme in Finland started in late 1993 and was linked to the problems of fish farming waste management, pioneered in Russia. The main aim was to experiment with the possibility of using artificial reefs in nutrient and biomass removal. The project studied whether the growth capacity of fouling communities in the Finnish Archipelago, Gulf of Bothnia was high enough to be used in catching significant amounts of nutrients released by the fish farms. Fish farming is an expanding industry in the Finnish Archipelago. Nutrients released due to overfeeding and fish faeces are causing eutrophication of the area. Different materials and reef structures were experimented with as substrata for filamentous algae and epifauna (Laihonen *et al*. 1997) The recruitment rate, growth rate and the efficiency with which nutrients are taken up by the fouling communities were recorded. Comparison of the nutrient amounts released by the fish farm in the experiment with the mass balance of the entire system were calculated. It appeared that the majority of the fouling community was algae and that the nutrient absorbed was not sufficient to make a significant reduction in the excess nutrient in the Finnish Baltic (Antsulevich *et al*., 1999).

The European Artificial Reef Research Network (EARRN)

The EARRN, started officially in May 1995, consists of 51 scientists from 31 laboratories throughout the EU and ran with EC (European Commission) funding for 3 years. It is still in existence, co-ordinated by Dr. Antony Jensen, School of Ocean and Earth Science, University of Southampton. A 5 day conference in late March 1996, focused on 4 topics: management of coastal resources (including fishery enhancement), socio-economic impacts and legal aspects of artificial reefs, research protocols and reef design and materials (Jensen, 1997a). The meeting was followed by a number of topic specific workshops which recommended scientific themes and actions (Jensen, 1997b, 1997c, 1997d,1998a; Whitmarsh *et al*., 1997). These were further developed in the final report (Jensen, 1998b) to the EC.

Future of artificial reef research in Europe

Effective reef design is one of the research topics of the future. Understanding the requirements of species with commercial and conservation value will become more important as managers develop a holistic approach to fisheries and nature conservation within the coastal zone. The socio-economic benefits of reef structures have yet to be assessed (although a start has been made) but diversification of coastal fishing community income sources appears, on a general level to be a sensible goal.

The problem of scale and functionality of artificial reefs has yet to be addressed. It has become obvious as discussion within EARRN has progressed that as yet we have no idea how large an artificial reef needs to be if it is to function as a self-sustaining ecosystem. We are aware that the European structures have not reached that scale as yet. The Japanese have an arbitrary volume figure (2500 m^3) below which they consider a fishing reef to be ineffective and a volume of 150,000 m^3 for a regional reef development (Simard, 1995). Research to establish the effective size of artificial reefs to accomplish a specific aim will be needed soon.

Currently artificial reef science continues to develop in Europe. Greece deployed their first major artificial reef in summer 1998, Denmark is considering artificial reefs seriously for habitat replacement, there is considerable interest in the UK and Norway in re-using steel jackets in a positive manner in the North Sea. There is renewed interest in France in developing artificial reefs. In the southern Mediterranean Tunisia has an interest in artificial reefs and in the Black Sea, Romania has developed artificial structures as biofilters to help in solving pollution problems. The established reef research countries are also pushing ahead with new ideas for aquaculture, habitat design and protection, tourism and the use of reefs as test beds for scientific experiments. All of this activity is aimed at producing a greater understanding of how artificial reefs can be used as an integrated management tool within the European coastal zone. It its final report to DG XIV the EARRN (Jensen, 1998) has outlined research topics (Table 1) important in future research proposals.

Many of these aspects interrelate, any single research project would involve a variety of differing topics. Research projects in the future should seek to produce quantified, comparable data that will lead to the construction of planned, targeted, designed and assessed artificial reefs. The development of such structures should involve socio-economists, engineers, scientists and local communities and users as well as those with responsibility for coastal management. For European artificial reefs to progress researchers must strive to reveal how reef systems work and how they may be manipulated to provide desired biological and socio-economic end-products. Artificial reefs are starting to be used as tools in Italy and Spain, but there is some way to go before reefs are accepted throughout Europe as effective and responsive tools in habitat management. The key to acceptance is the effective dissemination of knowledge gained through good quality research.

Table 1**.** Summary of future research topics recommended by EARRN.

Aquaculture	A1 Development of reef based aquaculture systems for coastal waters A2 Economic and social analysis of developing coastal mariculture A3 Development of equipment and methodology
Ranching	R1 An understanding of the habitat requirements R2 Reef Design R3 Economic appraisal R4 Legal assessment
Biomass Production	BP1 Survival of juveniles BP2 Linked to BP1 would come a consideration of food availability and value BP3 Energetic advantage BP4 Scale of habitat
Fisheries	F1 Fishery exploitation strategies F2 Protection of habitat F3 Fishery resource partitioning F4 Impact of a reef on existing fisheries
Reef System	RS1 Understand why reefs prove attractive to fish and other mobile species RS2 Predicting reef performance RS3 Energy flow through a reef system
Monitoring and Appraisal	MA1 Evaluation of socio-economic and technical performance MA2 Prove proposed EARRN monitoring programme in the field MA3 Appraisal and assessment of physical, biological and chemical parameters around artificial reefs
Recreation and Tourism	RT1 Design. Reef design will have to maximise the needs of the user community RT2 Socio-economic benefits
Materials	M1 Use of scrap tyres in artificial reefs. M2 Use of shipwrecks. M3 Re-use of steel jackets from oil production platforms M4 Development of concrete mixtures
Reef Design	RD1 Design to prevent trawling and/or encourage other fishing methods. RD2 Design to promote availability of food species (sessile or mobile). RD3 Design to provide specific habitat. RD4 Design to promote tourist benefit
Nature conservation	NC1 Biodiversity development. NC2 Scale of reef area – how big to have a measurable impact? NC3 Environmental assessment

Coastal breakwaters

Introduction

Many types of coastal defence structure, such as breakwaters, jetties, sea-walls and groynes, form a hard substratum of higher relief than the original seabed. Coastal structures that are submerged for at least part of the tidal cycle are available to be colonised by marine organisms, some of which may be commercially important, or significant in terms of nature conservation or increased biodiversity. Ecological aspects of man-made structures in the sea have been extensively studied in the context of artificial reefs (D'Itri, 1985; Pollard & Matthews, 1985; Stanton *et al.*, 1985; Seaman & Sprague, 1991; Berger, 1993; Grove & Wilson, 1994), but there is much less information about the ecological properties of coastal defence structures. ‘Hard’ coastal defence structures usually have an outer surface of quarried rock or concrete and are constructed nearer to shore than most artificial reefs, so that they are often partially or wholly exposed at low tide (Pethick & Burd, 1993).

Subtidal epibiota

With the advent of scientific diving, it became possible to extend surveys of marine life on coastal structures below the low water mark. Diving studies have described the species composition and abundance of attached organisms, or fish assemblages, or both. Since there are relatively few published studies of subtidal epibiota (attached organisms) on coastal structures, they are dealt with individually.

Following the construction of a storm surge barrier at the mouth of the Oosterschelde estuary (SW Netherlands) in 1976, long term surveys of the subtidal flora and fauna on artificial hard substrata in the Oosterschelde and the salt water Lake Grevelingen were carried out by divers from 1979 (Leewis & Waardenburg, 1989; Leewis *et al.*, 1989; Leewis & Waardenburg, 1991). From 0–3 m below mean low water, the growth was dominated by red and green algae and below this, attached animals dominated: mainly sea anemones, sponges, ascidians (sea squirts) and hydroids, with mussels, oysters and slipper limpets also present. There was a west to east change in species composition, reflecting changes in current velocity, wave impact and turbidity (Leewis & Waardenburg, 1991). Interannual variation in abundance and species composition of marine life was superimposed on these vertical and horizontal patterns of distribution. Differences were noted in colonization of different types of artificial substratum placed experimentally. Subtidal marine growth was greatest on limestone and concrete. Coverage was moderate on gneiss, basalt and various furnace slags, although organisms growing on the slags became contaminated with heavy metals. Marine growth was sparse on copper slag, probably due to copper toxicity, and on asphalt, possibly due to toxicity of polyaromatic hydrocarbons, or the viscosity of the material inhibiting settlement of marine organisms (Leewis *et al.*, 1989). The estimated biomass on hard substrata was proportionately greater than that in soft sediments (predominantly cockles and mussels) in the area (Leewis & Waardenburg, 1991).

Rankin Island is an artificial island in Santa Barbara Channel, California, linked to the shore with a 0.8 km causeway. It is a rubble mound structure, constructed in 1957–58 from rock with sandfill, with additional protection on the exposed side provided by concrete tetrapods. Water depths around the structure reach 14 m. In 1976–1977, the marine life on and around the structure was surveyed in transects from the upper splash zone to the seabed (Johnson *et al.*, 1978). By this time, considerable quantities of mussel and oyster shell debris had accumulated at the base of the placed material, adding to habitat heterogeneity. The structure was found to provide a diverse habitat in a previously relatively uniform environment, supporting several different species associations, according to depth, degree of exposure and siltation. There was heavy growth of mussels on the concrete tetrapods, but less on the sheltered sections. Abundance of most of the species varied seasonally. The total biomass on the structure was estimated to be over 300 times greater than that in the sediment prior to construction (Hurme, 1979).

Quarrystone jetties approximately 1 km in length with granite boulder armouring were constructed at Murrells Inlet, South Carolina, in 1977–80. Biological surveys of the surrounding seabed were carried out before, during and after jetty construction (Knott *et al.*, 1983) and biological colonization of the jetties was monitored by divers from the outset for five years (Van Dolah *et al*., 1984, 1987). Coverage, abundance, species diversity and vertical zonation patterns of attached organisms stabilised over the first year after construction, although seasonal and inter-annual changes in species composition were noted. Changes in sediment composition caused by the jetties resulted in increased intertidal species richness in sheltered areas, but this effect was not evident subtidally (Knott *et al*., 1983).

Two sites on Plymouth breakwater (Devon, UK) were examined by divers as part of a wider survey to assess the marine nature conservation value of Plymouth Sound, which was considered to be of national importance (Hiscock & Moore, 1986). The breakwater is 1.6 km long, with 0.35 km arms at each end, and was constructed from 1812 to 1851 using 4.1 million tonnes of limestone and 2.5 million tonnes of granite facings. The breakwater, particularly the seaward side, was colonised by species communities typical of the open coast. The sheltered (north) side of the breakwater was more silty, with lower species diversity and communities similar to those of extensive harbour walls elsewhere, although with boring (hole making) species characteristic of limestone. The sheltered seabed to the north of the breakwater consisted of fine mud with a very high biomass and species richness (Hiscock & Moore, 1986).

Breakwaters at Portland Harbour (Dorset, UK) were also inspected as part of the same series of nature conservation surveys (Howard *et al*., 1988). The Portland breakwaters were constructed in 1847–72 and in 1903 from Portland stone (limestone) and, in combination with the tidal regime and climate, they have created unusual conditions within the harbour, which support a unique assemblage of warm water and mud-dwelling species. A few sites on the insides of the breakwaters themselves were examined and these were found to have a dense growth of kelp and red ‘understory’ algae in the shallows, but were silty and rather barren below this; less so near the ship channels where there was greater water movement. There were surprisingly few crevice-dwelling species, but the rare black-face blenny (*Tripterygion atlanticus*) was observed. No lobsters were seen, but edible crabs (*Cancer pagurus*), velvet crabs (*Necora puber*), shore crabs (*Carcinus maenas*) and prawns (*Palaemon serratus*) were recorded (Howard *et al*., 1988).

Fish and crustaceans

The coastal structures studied have usually been inhabited by fish species typical of local rocky areas, often including species of importance to recreational fishermen (Johnson *et al*., 1978; Stephens & Zerba, 1981; Van Dolah *et al*., 1984; Lindquist *et al*., 1985; Burchmore *et al*., 1985; Ambrose & Swarbrick, 1989; Lincoln Smith *et al*., 1994; Stephens *et al*., 1994; Kumagi *et al*., 1995). Commercially important crustaceans have also been found on coastal structures. For example, American lobsters (*Homarus americanus*) were found in a rock breakwater in Rhode Island (Sheehy, 1976), the jetties at Murrells Inlet, South Carolina, were inhabited by Stone crabs (*Menippe mercenaria*) and lesser numbers of Blue crabs (*Callinectes sapidus*) (Van Dolah *et al*.,

1987) and a small population of European lobsters (*H. gammarus*) developed in rock armouring placed at the foot of dykes in the Netherlands (Havinga, 1951).

Some studies have compared fish communities on breakwaters with those on natural reefs and, as with artificial reefs (Bohnsack & Sutherland, 1985), it has often been found that population density and/or species diversity is greater on artificial structures than at natural sites (Lincoln Smith *et al*., 1994; Ambrose & Swarbrick, 1989; Stephens *et al*., 1994a). Ambrose & Swarbrick (1989) compared the species composition and abundance of fish found on natural reefs with three quarry rock breakwaters, an artificial island (Rincon Island) and several artificial reefs in California. The population density of fish on some breakwaters was greater than the average value for natural reefs, but lower on others. Since the natural reefs were generally much larger than the artificial structures, the overall abundance of fish was greater at the natural sites. Species diversity was generally greater on the breakwaters than the natural reefs and, for mid-water fish at least, was also greater than on the artificial reefs, which were of lower relief (Ambrose & Swarbrick, 1989).

In some cases, abundance or diversity of fish around breakwaters has been similar to or less than at local natural sites. A harbour wall, 2.5 km in length, made of concrete modules and large concrete blocks to a depth of 10 m in Botany Bay, Australia, had lower overall abundance and species diversity of fish than a nearby natural reef, although the attached flora and fauna were similar at the two sites (Burchmore *et al*., 1985). The greater age and structural complexity of the natural reef were thought to account for the greater number of fish species found there. The harbour wall had a slightly higher abundance of species of economic significance, however (Burchmore *et al*., 1985).

A number of authors have attributed the relatively high diversity of fish species on breakwaters to their greater vertical relief, compared with most artificial reefs and some natural reefs (Hurme, 1979; Stephens & Zerba, 1981; Ambrose & Swarbrick, 1989; Lindquist *et al*., 1985). Since some fish species inhabit particular depth ranges, a structure of greater height potentially accommodates a greater number of species. However, there is conflicting evidence in the artificial reef literature of the influence of structure height on the diversity and abundance of fish attracted (Bohnsack & Sutherland, 1985; Bohnsack *et al*., 1991). Height of structure may have a greater influence in shallower water. Another feature which contributes to biodiversity on artificial and natural structures is the growth of attached organisms, such as kelp and mussels. These species further increase habitat complexity and thereby accommodate a greater number of species of fish and other organisms (Reish, 1964; McCloskey, 1970; Hurme, 1979; Ambrose & Swarbrick, 1989; Rice *et al*., 1989; Yano *et al*., 1995b). Iwasaki *et al*. (1995) have attempted to model biological changes resulting from the construction of coastal defence structures in different regions of Japan.

Coastal structures are clearly capable of attracting fish, but an important aspect of their ecological and economic significance is whether they increase the production of fish biomass. Assessing this is not straightforward, since it is necessary to show not only that the artificial habitat promotes growth, survival or reproduction of fish, but also that the local natural habitat is limiting in these respects (Polovina, 1991). In other words, does the population at large gain a net benefit from the artificial habitat (Grossman *et al*., 1997)? A first step in this process is often to determine whether fish obtain nutritional benefit from the artificial structure. Where stomach contents have been examined from fish collected near coastal structures, there has been evidence that some species feed on organisms growing on the structure, or feed on other fish that have fed on organisms growing on the structure (Hastings & Bortone, 1980; Lindquist *et al*., 1985; Van Dolah *et al*., 1987). There is also evidence that coastal structures may accommodate reproduction and recruitment of some species, by providing spawning or nursery habitats (Liston *et al*., 1985; Van Dolah *et al*., 1987; Stephens *et al*., 1994; Kumagi *et al*., 1995; Yano *et al*., 1995b).

Fishing and aquaculture

There are few published studies quantifying the use of coastal defence structures in fisheries or aquaculture, although several authors note the importance of breakwaters or jetties for recreational fishing (Hedgpeth, 1953; Hastings, 1978; Hurme, 1979; Van Dolah *et al*., 1984; Alveras & Edwards, 1985; Buckley, 1985; Binkowski, 1985; Hawkins & Cashmore, 1993; Ozasa *et al*., 1995; Takaki *et al*., 1995) and some for commercial fishing (e.g. Havinga, 1951; Binkowski, 1985; Smith, 1990; Ozasa *et al*., 1995).

Van Dolah *et al*. (1987) studied patterns of recreational fishing around the jetties at Murrells Inlet, South Carolina, by observation and questionnaire survey. There was considerable fishing activity around the structures throughout the year, both from one of the jetties which had an asphalt walkway and from small boats. Not surprisingly perhaps, recreational fishing activity was greater at weekends; during the summer, the overall level of fishing increased and week day fishing became more prevalent. Correspondingly, the quantity of fish and number of species caught by fisherman were greatest during the summer. More fish were captured in proximity to the jetties than elsewhere. It was concluded that the jetties had clearly improved sport fishing opportunities in the area, which was likely to have had a significant beneficial effect on the local economy, which relied heavily on spending by tourists. In contrast, the crab populations inhabiting the jetties were probably insufficient to sustain a substantial fishery (Van Dolah *et al*., 1987).

In the Netherlands, a fishery for lobsters (*H. gammarus*) developed at the turn of the century after they colonised rock armouring newly placed at the foot of dykes in areas of strong tidal streams (Havinga, 1951). Edible crabs, *Cancer pagurus*, were also found at the foot of the dykes but were not commercially important. Catches of lobsters increased until the mid 1920s then fell, probably as a result of overfishing. More recently, commercial fishing is again being licensed on a small scale, after a period of prohibition to allow the population to recover from a drastic decline during the severe winter of 1963 (Leewis, personal communication).

Structures constructed primarily for coastal defence may have incidental effects on fisheries or aquaculture, through changes in water conditions or sediment dynamics. These changes may be beneficial or detrimental. For example, a breakwater extension at Tomakomai port in Japan was followed by increased catches of clam (*Spisula sachalinensis*), which were thought to be due to changed circulation patterns affecting larval distribution and sediment composition (Yano *et al*., 1995a). In contrast, construction of a storm surge barrier in the Oosterschelde estuary, Netherlands, resulted in the loss by flooding of a large area of intertidal mussel and oyster cultivation ground (Dijkema & van Stralen, 1989). Although dykes in the Netherlands provide hard substrata which could be used for culturing mussels or kelp (Richards, 1990), they have not been used for this (Leewis *et al*., 1989). In Japan, breakwaters have been constructed, often of interlocking concrete modules, specifically to create sheltered areas for various forms of fishery (Hasegawa & Shimizu, 1995) and aquaculture (Mottet, 1985; Takaki *et al*., 1995; Yoshino *et al*., 1995), and to protect sensitive habitat of commercially important species from damaging wave action (Mottet, 1985). Breakwaters have also been used as a substratum for culture of seaweed or trapping weed for use in urchin and abalone culture (Mottet, 1985). Techniques have been developed in Japan to promote seaweed growth on breakwaters by impregnating concrete with ferrous sulphate, to reduce alkalinity caused by leaching of calcium hydroxide and to provide iron nutrients (Hotta *et al*., 1995).

Structure design

The Port and Harbor Bureau of the Japanese Ministry of Transport has a policy of designing port structures that provide habitat for marine organisms, in addition to fulfilling their primary function (Ozasa *et al*., 1995). This policy has been implemented by constructing breakwaters designed to encourage growth of seaweed, in the expectation that this will provide spawning, nursery and feeding habitat for fish and shellfish, including commercially important species (Akeda *et al*., 1995; Takaki *et al*., 1995; Yano *et al*., 1995b). Composite coastal defence structures have been designed, consisting of a primary breakwater or jetty, which may be a concrete structure on a rubble foundation, with a submerged rubble breakwater some distance offshore from the main structure and existing kelp beds (Akeda *et al*., 1995; Hasegawa & Shimizu, 1995). The profile of the offshore structure has been designed to maximise seaweed growth, as well as to reduce wave action in the area between the structures (Akeda *et al*., 1995; Yano *et al*., 1995b). The port authority in Vancouver, British Columbia, Canada, also has a policy of maximising the biological value of port structures, which is implemented by increasing habitat heterogeneity through modifications to the design of port structures and the construction of additional artificial reefs (Desjardin *et al*., 1995). The design of a 4 km rip-rap sea wall in Manhattan, New York, was modified to create overwintering habitat for striped bass, *Morone saxatilis* (a valuable species fished commercially and recreationally), by selecting quarry rock size to create appropriate interstitial spaces and by constructing ‘underwater jetties’ to provide areas of shelter from the current (Alveras & Edwards, 1985).

The extent and diversity of artificial reef studies provide useful information when considering design modifications of coastal defence structures for ecological or fisheries applications. Different designs of artificial reef have been created by deploying prefabricated modules of particular shape, size and materials; by assembling components regular in shape but not specifically designed for artificial reef use, such as used vehicle tyres, in particular configurations; or by controlling the size distribution and placement of irregular constituents, such as quarried rocks (Seaman & Sprague, 1991). Considerable expertise exists in engineering aspects of artificial reef design, such as material properties, structural integrity and stability, which has no doubt been drawn largely from other branches of maritime civil engineering, such as coastal defence. However, there is much less information about the habitat requirements and preferences of species that structures are intended to accommodate (Grove *et al*., 1991; Spanier, 1997; Seaman, 1997b). Often a pragmatic approach has been adopted, in which structures have been designed with general aims, such as raising the profile of the seabed, creating hard substratum in areas of sediment, or increasing habitat complexity, in the expectation or hope that they will attract fish and/or support growth of sedentary marine life. Since fish and attached marine organisms appear to be attracted to a wide range of underwater structures (Seaman & Sprague, 1991), this approach has frequently been deemed satisfactory by users seeking a tangible benefit, when judged by rather non-specific criteria, such as an increase in the concentration or catch of fish (Bohnsack & Sutherland, 1985). However, this utilitarian approach does not in itself help greatly in optimising reef design for particular target species or species assemblages (Seaman, 1997a).

Information about the influence of reef design on reef ecology can be obtained retrospectively by comparing the biological performance of different types of artificial reef, although these comparisons are often confounded by geographical variables (Bohnsack *et al*., 1991). More rigorous comparisons have been made in field experiments, in which different designs have been deployed in the same locality at the same time, specifically to investigate relationships between structure design and colonization by reef organisms (e.g. Sheehy, 1976; Sheehy & Matthews, 1985; Spanier *et al*., 1988; Bell *et al*., 1989; Feigenbaum *et al*., 1989; Hixon & Beets, 1989; Beets & Hixon, 1994; Bohnsack *et al*., 1994; Bortone *et al*., 1994; Frazer & Lindberg, 1994; Lozano-Alvarez *et al*., 1994; Mintz *et al*., 1994; Seaman *et al*., 1995; Herrnkind *et al*., 1997). Logistical considerations usually mean that such experimental studies are carried out on a small scale (Seaman, 1997a). Another approach to studying the biological effects of artificial reef design has been to modify the characteristics of an existing structure, by increasing structural complexity for example, and monitoring changes in fish abundance or species composition, with suitable experimental controls (e.g. Gorham & Alevizon, 1989).

A diverse array of prefabricated modules, usually of concrete, steel or, more recently, glass reinforced plastic, has been used in artificial reefs, particularly in Japan, where the national government pursues a policy of increasing the productivity of marine living resources through technological intervention (Stone *et al*., 1991). In Japan, government subsidies for artificial reef construction are dependent on adherence to detailed guidelines on materials, design and deployment (Grove *et al*., 1991). Considerable emphasis is placed on the visual and hydrodynamic properties of artificial reefs in conjunction with categorization of fish species according to the position they typically occupy in the water column and their degree of association with reefs (Nakamura, 1985). Structural components are designed on the basis of information about the limits of fish visual acuity, although the general applicability of these limits to reef fish is unclear. Japanese studies suggest that the attractiveness of a submerged reef to fish, particularly at night, depends on the extent and nature of turbulence caused when tidal currents flow over the structure. The influence of reef properties, principally height in relation to water depth, on water movement has been investigated with sonar and structures are designed to optimise turbulence, in terms of upwelling, vortex shedding or maximum current speeds in the lee of the structure (Stone *et al*., 1991).

Some artificial reefs of quarry rock have been designed for particular target species. For example, in California, a boulder reef was constructed with the aim of promoting growth of giant kelp (*Macrocystis* sp.) (Jessee *et al*., 1985). Unfortunately, kelp did not grow well on the relatively high piles of rocks, but flourished on isolated boulders and at the bases of the reefs. It was subsequently discovered that *Macrocystis* survival depends on the intensity of grazing by fish, which are less abundant on low profile reefs (Patton *et al*., 1994), illustrating the dangers of considering single target species in isolation. An artificial reef of quarried sandstone rocks was deployed in the Gulf of Saint Lawrence, eastern Canada, specifically for American lobsters in 1965 (Scarratt, 1968). Quantitative information on lobster shelter requirements did not exist at that time, but a range of rock sizes was used to create crevices suitable for a range of lobster sizes. Within weeks of construction lobsters moved to the site from nearby natural habitat and over the following eight years the size distribution of lobsters approached that of those in natural habitat, but biomass density appeared to be greater on the artificial reef (Scarratt, 1973). Recently, an artificial reef was constructed in Narragansett Bay, Rhode Island, to provide new habitat for lobsters (*H. americanus*) in compensation for damage to lobster stocks caused by an oil spill (Cobb *et al*., 1998). The reef has been designed to investigate differences in colonization of two different grades of substratum (10–20 cm stone and 20–40 cm stone) by lobsters and changes in population parameters over time will be monitored and compared with nearby natural habitat.

Increasingly, it is recognised that the success of an artificial reef depends on clearly defining its purpose at the outset (Seaman, 1997b). Accordingly, attempts are being made to design artificial reefs that correspond more closely with the habitat preferences of target species (Spanier, 1995, 1997). One way of achieving this is to design artificial structures that mimic features of natural habitat that appear to be important to the ecology of target species (e.g. Patton *et al*., 1985, 1994; Herrnkind *et al*., 1997), particularly those that reduce mortality at critical life history stages (Bohnsack *et al*., 1997).

Perhaps owing to the obvious association of several species of lobster with rocky substrata, in combination with their economic value, habitat preferences of clawed (Nephropidae), spiny (Palinuridae) and slipper (Scyllaridae) lobsters have been investigated with field observations and aquarium shelter selection experiments. In American lobsters, there is a strong relationship between various dimensions of occupied shelters and the body size of the resident lobster (Cobb, 1971; Wahle, 1992). Several studies have shown that shelters provide protection from predation (Smith & Herrnkind, 1992; Wahle & Steneck, 1992; Barshaw & Spanier, 1994) and in spiny lobsters (*Panulirus argus*), Eggleston *et al*. (1990) showed that the degree of protection depends on shelter size relative to body size.

Choice tests under controlled conditions indicate some common features of shelter preference among the different species of lobster studied. Preferred shelters provide overhead cover and shading, are usually wider than high, have more than one opening and openings are smaller than the internal dimensions of the shelter (Cobb, 1971; Spanier & Zimmer-Faust, 1988; Spanier *et al*., 1988; Spanier & Almog-Shtayer, 1992). These have been interpreted as anti-predator features, although in the case of clawed lobsters, they may also aid the resident in intra-specific competition for shelters. Spiny and slipper lobsters lack the powerful chelae of clawed lobsters and have an alternative defensive tactic of gregariousness and, in spiny lobsters, communal defence using their spiny antennae (Kanciruk, 1980). Shelter selection in these species is influenced by the presence of conspecifics and appears to promote cohabitation of shelters (Eggleston & Lipcius, 1992; Mintz *et al*., 1994; Eggleston *et al*., 1997). Juvenile American lobsters become less selective when choosing a shelter in the perceived presence of a predator (Boudreau *et al*., 1993), but this does not diminish the value of identifying the optimum shelter dimensions for protection from predators.

Computer modelling techniques have been developed to predict the size distribution of crevice openings (Caddy & Stamatopoulos, 1990; Barry & Wickins, 1992) and the size distribution and inter-connectivity of interstitial spaces (Wickins, 1995) produced in an artificial reef or coastal defence structure comprising a given mix of rock sizes. Knowing the shelter sizes preferred by crevice-dwelling target species such as lobsters, it should be possible to determine the mix of rock sizes required to create suitable habitat (Barry & Wickins, 1992; Wickins & Barker, 1997).

Conclusion

Coastal defence structures provide new habitat that sometimes supports prolific growth of attached algae and invertebrates, and attracts fish and mobile invertebrates, potentially increasing local biodiversity and enhancing production of some species, depending on limitations on natural habitat in the area. As with artificial reefs, it is often not clear whether coastal structures simply concentrate existing populations of fish, or whether they contribute to enhanced fish production. This is an important issue with regard to how fishing on structures is managed, but is difficult to resolve, since it requires information on the effects of structures on the growth, survival and reproduction of fish at large in the area and not just at the structures themselves.

There may be scope for modifying the design of coastal defence structures to accommodate particular reef species of interest, without compromising the primary coastal defence function. However, there is insufficient information about habitat requirements of many likely target species and about the influence of physical habitat on interactions with other species, such as predation and competition, to allow the ecological properties of structures to be optimised rationally. Lobster shelter preference studies may provide a useful model for identifying habitat requirements of reef organisms in three phases. Characteristics of natural habitat used by the species of interest can be quantified and compared with available habitat. This information is then used as a basis for aquarium investigations of habitat preferences and selectivity under controlled conditions. The findings of these aquarium studies can then be confirmed or modified by field experiments in a more realistic setting, before being incorporated into the design of coastal structures. As with artificial reefs, post-deployment monitoring would be necessary to provide information about the biological performance of structures, which can feed back into the future design.

The use of artificial reefs in crustacean fisheries enhancement[1]

Introduction

Attention has focused on crustacean aquaculture throughout the world because of the high value and ready market for the crop. Attempts have been made to culture the clawed lobsters *Homarus americanus* (USA and Canada) and *Homarus gammarus* (Europe). Success in laboratory experiments in North America led to pilot schemes to culture these species of clawed lobster to market size in captivity. Although technically feasible it was found to be uneconomic because the animals took years to reach market size and the cost of the labour required was high. *Homarus* spp. are best reared in individual compartments (e.g., Waddy, 1988; Beard and Wickins, 1992), as they are aggressive towards each other, which involves individual feeding of each animal. Fishery stock enhancement still remains a possibility, through release of hatchery reared juveniles, habitat provision or a combination of the two, leading, ultimately to the ranching of clawed lobsters on artificial reefs.

Stock enhancement

The release of juvenile, hatchery reared, clawed lobsters is not new but until recent work in the UK none of the previous stock enhancement schemes had effectively monitored return of hatchery reared animals in the commercial catch (Bannister *et al*. 1994). Enhancement, especially in the USA, was undertaken with an optimistic philosophy - adding juveniles cannot do obvious harm and it may well do some good. Other opinions, for example, that the release of hatchery reared juveniles in the vicinity of reefs may harm natural populations by attracting predators, were generally ignored.

Between 1983 and 1988 the MAFF (Ministry of Agriculture, Fisheries and Food) hatchery reared 49,000 juvenile lobsters; these were tagged with microwire tags and released into the wild off Bridlington (NE England) (Bannister *et al.*, 1994). This programme was designed to evaluate the potential for natural stock enhancement of lobster populations in the UK and was the first such programme to utilise microwire tags. Released lobsters reached legal size (85 mm carapace length ,CL) in 4 to 5 years, showing individual variation in growth rates, and have been recaptured up to 8 years after release. Survival estimates average between 50% and 84% of releases. Recaptures revealed that the lobsters showed site fidelity, most being caught within 6 km of the release site. Some recaptured females carried eggs, showing that hatchery reared lobsters can contribute to the spawning stock.

This work has significant implications for ranching of lobsters on artificial reefs; it shows that juveniles will survive and mature into fishery sized animals within 5 years or so and that the site loyalty seen in adult lobsters elsewhere is also part of the juvenile behaviour pattern. The economic returns of such an operation depend on the cost of rearing and releasing juveniles being less than the profit made by fishermen capturing adults 4-5 years later. At present the economics appear to suggest that a profit would be made, a margin that could be increased by reducing the hatchery costs.

[1] This section is edited and reprinted with permission of the authors and EARRN from Jensen & Collins (1997)

Artificial reefs and lobsters: research to date.

It appears that at least 4 countries, Canada, Israel, the USA and the UK have focused attention on artificial reefs as a specific lobster habitat. Canada built the first artificial reef specifically for lobster research in 1965 from quarry rock placed 400 m away from minor lobster habitat, 2 - 2.5 km from major concentrations of lobsters (Scarratt, 1968; 1973). Over the following eight years the lobster population of the artificial reef was monitored by diving scientists. The reef was initially colonised by large specimens of the lobster (*Homarus americanus*) (>41 mm CL) thought to have outgrown their burrows, so being forced to roam to seek new shelter. By 1973 the size frequency distribution of the artificial reef population was similar to that on natural reefs in the area. Scarratt (1973) concluded that the standing crop on the reef might be increased by a different configuration of rocks but that a cheaper source of reef material or a multiple use reef would be needed before an artificial reef could be considered an economically viable proposition.

Artificial shelters have been considered as lobster habitat in the USA (Sheehy, 1976). Lobster numbers inhabiting the single and 3-chambered shelter units were greater than found in natural reefs, and showed similar, or greater, densities to the artificial reef populations described by Scarratt, 1973. Abundance per unit area was a function of shelter spacing and number of compartments per shelter. The importance of inter-shelter spacing in determining lobster abundance suggested that nearest-neighbour distance for juveniles lobsters may be an important aspect of maximising the stock of an artificial habitat.

In Israel, efforts have focused on the slipper lobster, *Scyllarides latus*, an important commercial species found off the Mediterranean coast (Spanier, 1991). These unclawed lobsters were found to inhabit tyre artificial reefs. Research showed that slipper lobsters preferred horizontal shelters with two narrow entrances on the lower portion of the reef. Shelter response is believed to be a major defence mechanism for these animals (Spanier *et al.*, 1988) and the presence of the artificial reef provided new and suitable habitat for colonisation. Slipper lobsters migrate into deeper water as the temperature rises but tagged individuals were seen to return to the tyre reef over a 3 year period (Spanier *et al.*, 1988). Spanier (1991) suggests that, in the long term, populations of these heavily exploited animals could be protected by building appropriately designed artificial reefs for slipper lobsters in protected areas such as underwater parks and reserves.

In the UK work has been undertaken from 1988 to date on an experimental reef placed in Poole Bay on the central south coast of England. Deployed on a flat, sandy seabed in 1989, this reef, 3km from lobster habitat, was constructed from blocks of stabilised Pulverised Fuel Ash (PFA) to establish the environmental suitability of PFA in British waters (Collins *et al.*, 1991a). One aspect of this study was to assess the potential of reefs for fisheries enhancement. Within 3 weeks of deployment lobsters (*Homarus gammarus*) were present on the reef (Collins *et al.*, 1991). Tagging studies were initiated in 1990 and data to February 1994 shows that lobsters have found the artificial reef a suitable long term habitat; the longest period of residence stands at 1050 days (Jensen *et al.*, 1994b). Conventional tagging of sub-legal size (<85 mm CL) lobsters in the nearby Poole Bay fishery revealed that lobsters in the Poole Bay area did not undertake any seasonal migration, and that most movements averaged over time were less than 4 km in magnitude (Jensen *et al.*, 1994b). The use of a novel electromagnetic telemetry system on the Poole Bay Artificial Reef has started to reveal complex local movement behaviour, with nocturnal movement dominating, frequent changes of daytime refuge, multiple occupancy of the conical (1 m high and 4 m base diameter) reef units and some animals leaving the reef site for up to 3 weeks and then returning (Collins *et al.* in prep).

Diver observations and evidence from pot caught lobsters suggest that the Poole Bay artificial reef can support all aspects of the lobsters benthic life cycle: berried females utilise the shelters, some reproducing more than once on the reef; lobster stage 4 larvae have been taken from the waters above the artificial reef; a 27 mm CL individual was caught in a "prawn pot" on the reef (it is likely that this lobster settled on the reef as a stage IV larvae); and a wide size range of juvenile and adult animals have been captured and/or observed by diving scientists. Comparisons of the size frequency distribution of the Poole Bay fishery lobster population and that of the artificial reef have show statistically significant differences between the two groupings. This is thought to be due to the much larger proportion of the fishery population being of 80 - 85 mm CL (just below legal landing size) than on the artificial reef. This reflects the greater proportion of 85 mm CL and above animals on the artificial reef. Whilst fishing mortality is lower on the reef than in the fishery it is felt that this difference is in some part due to the greater proportion of large niches on the artificial reef in comparison to the natural reefs in Poole Bay.

Discussion

The role of artificial reefs in lobster stock enhancement is one of providing habitat. This can either be the creation of lobster habitat where none had existed before or the modification of natural habitat to, say, provide an increased number of suitable shelters for lobsters in general, or of a given size range. It is considered feasible to design a reef and provide the required shelters in sufficient numbers and size to minimise "off-reef" movement caused by the need to seek a new shelter after moult. Barry and Wickins (1992) have published models that predict the number and size of shelters in a reef made up of perfect spherical boulders, a starting point for more realistic material dimensions. Such a purpose built reef would also have to take into account foraging space requirements, stock density limitations and food supply. Design features do not have to just focus on lobsters; provision of a structure on the seabed will attract fish to the area and different species will be preferentially attracted by different types of reef profile (see Spanier, 1995).

Artificial reefs have been shown to effectively support at least four species of commercially important lobster. Questions have been raised about dilution of the natural population by increasing the habitat in a fishery by provision of an artificial reef. This would only be an initial effect before all niches were occupied, and could be minimised by careful siting. Work by Jensen *et al.* (1994a) suggests that few *H. gammarus* (<85 mm CL) would move more than 4 km from their original capture location. A remote artificial reef could be supplied with hatchery reared juveniles with a good prospect of survival, such as seen in juvenile release experiments in the UK (Bannister *et al.*, 1994). At present the maximum densities of lobsters that can be achieved have not been established, but data presented by Scarratt (1973) for *H. americanus* suggests that the Canadian quarry rock reef supported 1 lobster per 6 m^2 whilst the Poole Bay reef is thought to hold an individual *H. gammarus* per 2 m^2. Neither structure was designed to maximise lobster habitat.

The economics of artificial reef construction are still being debated. The use of high technology concrete and steel structures with large scale construction techniques does not seem to be feasible in a UK context at present, where there is emphasis on the lobster fishing "industry" (a collection of small "one person" businesses) paying fully for such structures. Grant aid from the European Commission is possible; the EC supported 50% of Italian and Spanish and 89% of French reef construction costs in the past (Bombace *et al.*, 1993), but this funding has yet to be explored from a UK context. Perhaps more realistically from a fisherman's point of view, would be the use of environmentally acceptable "materials of opportunity" like quarry rock and low cost stabilised waste products such as cement stabilised Pulverised Fuel Ash (PFA). Such materials could be deployed by a combined effort from fishermen, over a period of time, to create properly planned, multiple function fishing reefs at a low cost. Recent (1997) UK legislation extends the several order fishery regulations in England and Wales to include lobsters within the definition of “shellfish”, to allow aquaculturalists and fishermen to have sole harvesting and fishing rights for lobsters on an artificial reef that they have created. This has removed a major disincentive to the development of lobster ranching or stock enhancement programmes utilising artificial reefs. It is hoped that this modified legislation will encourage reef development for shellfish ranching.

Whilst it has been shown that artificial reefs can support lobster populations over significant periods of time, many questions regarding the way lobsters utilise a habitat remain to be answered. In order to maximise stocking densities and minimise "off-reef" movement, lobster behaviour needs to be studied in greater detail. In the UK context this may include continuation of electromagnetic telemetry studies to detail localised behaviour and the deployment of an artificial reef designed to test some of the hypotheses of shelter size and density created during the past 5 years research. In a wider context both spiny and slipper lobster are important catches in European wild fisheries. Both animals have shown a willingness to exploit artificial habitats and research effort needs to investigate what ranching opportunities exist. With the popularity of seafood in Europe, and the potential to reduce imports of such valuable species and possible develop exports in time, lobster ranching using artificial reefs seems to be a research target with significant social and economic benefits to coastal communities.

Offshore windfarms & breakwaters

The development of offshore windfarms incorporating breakwaters offers interesting and novel habitat creation and coastal zone management opportunities. The Danish are also in the process of considering the habitat enhancement possibilities of windfarm breakwater placement.

That a breakwater will become colonised by marine life is not in doubt, it is likely to have a well-developed marine community within five years. However by influencing the position, shape and physical design of the breakwater a more targeted outcome than the general boulder community expected may be achievable.

The position of the breakwaters will, undoubtedly, be primarily driven by factors associated with power generation and transmission to land but secondary considerations might involve:

(1) Positioning the breakwater to facilitate some of the following:

- (i) Exploitation by inshore commercial static and/or mobile gear fishermen.
- (ii) Use by recreational anglers and or divers.
- (iii) Development of offshore seabed ranching and/or suspended/cage aquaculture
- (iv) Exclusion of trawlers from an area, within fisheries legislation, to protect sensitive habitat, facilitate the use of static (often more selective than mobile gear) gear or protect aquaculture initiatives.
- (v) Exclude all fishing effort to create a 'no-take' zone
- (vi) Influence water currents to promote settlement of larvae in a selected area.

(2) Influencing the material used to construct the breakwater to provide designed, targeted habitat:

- (i) Habitat creation targeted at identified species, e.g. fish for anglers
- (ii) Structural designs to enhance recreational diving.
- (iii) Habitat designs to allow lobster ranching using hatchery releases.

The possibilities are many but will be reduced by power generation requirements, fisheries legislation, political requirements and the opinions of other 'stakeholders' in the marine environment.

Experience suggests that the process of planning and developing breakwaters should involve a full stakeholder dialogue, so minimising problems as the project develops. This would run in parallel with feasibility studies of a variety of sites and a full (biological, physical, chemical and geological) baseline appraisal of selected sites, together with their existing and future uses. Such data will be essential if the full benefit is to be gained from each breakwater deployment.

Management of a breakwater development will be essential to gain the maximum return. If the breakwater is to be developed as a fishery area then effort and gear limitation my well be needed to ensure sustainability of function. Other scenarios will require other management techniques to be developed.

Creation of secondary benefits from a windfarm breakwater seems eminently feasible but what benefits and how they are achieved remains an important question in the project development phase.

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